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UNMANNED AERIAL VEHICLE HEAVY FUEL ENGINE TEST

FINAL REPORT

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13. ABSTRACT *(Maximum 200 words)*

This report documents the test results of three heavy fuel engines designed to demonstrate that Unmanned Aerial Vehicle operational requirements can feasibly be met utilizing heavy fuels (JP-5, JP-8 and Diesel) versus gasoline. The three engines included rotary engines delivered by AAI Corporation and Defense Group Industries Incorporated and a two cylinder, two stroke engine delivered by Southwest Research Institute. The testing was conducted at the Naval Air Warfare Center Aircraft Division Trenton during the period of 17 April 1992 through 22 January 1993.

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1.0 INTRODUCTION

This report documents the results of validation testing of three contractor developed engines designed to meet the goals of the Naval Air Warfare Center Aircraft Division, Trenton (NAVAIRWARCENACDIVTRN) fifty pound Heavy Fuel Engine (HFE) program. As authorized in reference (1), NAVAIRWARCENACDIVTRN performed the validation testing to ascertain the extent to which the HFE program goals (defined below) were achieved, and to define deficiencies and areas requiring further development for each engine.

Due to the low flashpoint temperature of gasoline (less than -40°F) and the difficulty in supporting gasoline logistically, the Department of Defense (DoD) policy requires the elimination of gasoline from the battlefield. In support of this decision, NAVAIRWARCENACDIVTRN solicited proposals to develop Unmanned Aerial Vehicle (UAV) engines to meet the following HFE program goals:

- 50 horsepower (HP) maximum rated power
- 0.5 lb/HP-hr brake specific fuel consumption (BSFC)
- 50.0 lbs maximum core engine weight (not including cooling radiators, alternator, propeller, muffler, etc).
- 300 hour durability
- 7,500 ft altitude starting capability
- Sea level to 15,000 ft altitude capability
- -25°F to 125°F ambient temperature engine operation
- JP-5, JP-8, and Diesel fuel operational capability

These HFE goals were defined based on the propulsion system requirements envisioned for fixed wing subsonic UAVs weighing 500 lbs or more.

The current state of the art for production heavy fuel engines includes only true compression ignition diesel engines and gas turbine engines. Unfortunately, the best production diesel engines in the 50 HP class weigh 250 lbs or more, although these engines can meet the remaining requirements listed above. Production gas turbine engines in the 50 HP class can meet all the above requirements with the exception of 0.5 lb/HP-hr BSFC. This is due to the poor sealing of the rotating components in the small diameters necessary to produce only 50 HP. Generally, as the diameter of the gas turbine engine is increased, the ratio of internal air leakage to total airflow decreases, causing efficiency to increase (decreased BSFC). Because of these limitations, a production diesel or gas turbine engine could not meet all of our program goals, necessitating the need for other engine types to be investigated.

Three contractors were selected for award from the HFE program solicitation. These were Southwest Research Institute (SwRI) located in San Antonio, TX, AAI Corporation located in Hunt Valley, MD, and Defense Group Industries Incorporated (DGII) of Arlington, VA. Each contractor pursued a structured technology development program culminating in the delivery of a concept validation engine to NAVAIRWARCENACDIVTRN.

The AAI and DGII engines were tested in NAVAIRWARCENACDIVTRN altitude test chamber 6W. The SwRI engine was tested in the Accessories Test Area (ATA) sea level test area designated B-Room. The AAI engine was tested from 17 April 1992 to 20 May 1992 and again from 9 November 1992 to 22 January 1993. The DGII engine was tested from 1 September to 14 October 1992. The SwRI engine was tested from 8 June 1992 to 29 December 1992.

2.0 DESCRIPTION OF TEST EQUIPMENT

2.1 ENGINES

2.1.1 AAI

The engine delivered for test by AAI was designed and manufactured by Norton Motors Limited located in Lichfield, England. Norton Motors (now known as Alvis UAV Engines, Ltd.) manufactures a complete line of Wankel-type air and liquid cooled engines in both single and dual rotor configurations. The primary use of these powerplants includes light manned aircraft and UAV applications. The engine delivered by AAI was derived from the production Norton model NR 801 single rotor liquid cooled gasoline engine. This engine was then extensively modified by AAI in conjunction with Norton Motors to operate on heavy fuels.

The AAI engine is a turbocharged, liquid and air cooled, single rotor, Wankel-type rotary engine with a total displacement of 298.0 cubic centimeters (cc). The engine was modified to operate on heavy fuels (JP-5, JP-8, and Diesel) as follows: (a) a Lloyd Conditioned Compression Ignition (patent pending) system consisting of a pilot and a main injector was installed, (b) the spark plug was replaced with a glow plug, (c) a prechamber was installed in the trochoid housing, and (d) the compression ratio was changed by modifying the rotor pocket.

The Lloyd Conditioned Compression Ignition system operates as follows: the pilot injector functions to initiate burning in a small pre-chamber by injecting a small amount of fuel that ignites and produces turbulence in the combustion chamber. Once the turbulence is generated, the main injector opens, allowing the fuel to mix with the swirling air and ignite the mixture at the ignition source. A glow plug powered by 12 VDC remains on during operation to assist in the combustion process. The fuel injection system uses a positive displacement, engine driven fuel pump and injects fuel directly into the combustion chamber at 1750 psig. The engine is equipped with a variable inlet guide vane turbocharger which provides a one atmosphere pressure boost (14.7 psig) at all speeds throughout the operational RPM range. A crankshaft driven metering pump is used to inject two stroke lubricating oil directly into the rotor bearings and into the intake air. A rear mounted, belt driven blower is used to force cooling air through the rotor bearing housing while the trochoid housing and end plates are liquid cooled with a water/ethylene glycol mixture.

The engine was designed to have an operational speed range from 3000 to 8000 RPM. The engine operates unthrottled, with the engine speed controlled by the quantity of fuel injected. The injection timing and duration are controlled by an electronic control unit (ECU) which operates a high speed solenoid valve (HSV) located on each of the fuel injectors. The ECU receives inputs of actual engine speed and engine rotor position and refers to an internal erasable programmable read only memory (EPROM) chip to determine optimal fuel injection timing and duration. The memory is programmed for a specific propeller load curve and can be replaced with appropriate EPROMS for various propellers. ECU control can also be in real-time (temporarily modifying the EPROM) when a personal computer is connected to the ECU. A summary of engine design characteristics are as follows:

Contractor Name:	AAI Corporation
Engine Manufacturer:	Norton Motors Limited
Engine Type:	Wankel-type Rotary
Configuration:	Single Rotor, Turbocharged
Combustion Type:	Lloyd Conditioned Compression Ignition
Combustion Chamber:	Prechamber in trochoid housing
Displacement:	298.0 cc

Compression Ratio:	
S/N 0101	8.0:1, 8.8:1
S/N 0102	8.8:1
Direction of Rotation:	CCW viewed facing PTO shaft
Maximum Power Output:	32.0 HP at 5900 RPM
Overspeed Limit:	8000 RPM
Idle Speed:	3000 RPM
Fuel Consumption:	0.44 lbs/HP-hr at maximum power 0.42 lbs/HP-hr at cruise power
Engine Dry Weight:	71 lbs w/o alternator and propeller
Ignition System:	Continuous operation 12 VDC glow plug
Starting System:	External hand held starter motor
Fuel Inj. Pressure:	Main: 1750 psig Pilot: 1750 psig
Fuel Inj. Pump:	BKM model RV-04I
Fuel Injectors:	Main: BKM part # 610469 Pilot: BKM model # 610468
Turbocharger:	Aerodyne Dallas model 63000 Series 057
Turbo Inlet Temp:	1700°F Maximum
Trochoid Housing Mtl:	Aluminum Alloy
Rotor Material:	Cast Iron
Cooling:	Liquid cooled engine housing (50/50 mix of water/ethylene-glycol), forced air and oil cooled rotor bearing, oil cooled turbocharger
Rotor Cooling Air Temp:	310°F Maximum
Engine Coolant Temp:	210°F Max (thermostat opens @ 190°F)
Lubrication:	Crankshaft driven oil metering pump for rotor bearing and apex seals (Total Loss System)

Lubricating Oil: Golden Spectro Synthetic Two-Stroke Oil

Fuel: JP-5, JP-8, and Diesel

2.1.2 DGII

The engine delivered for test by DGII was designed and manufactured by Wankel GmbH located in Lindau, Germany. Wankel manufactures rotary engines for stationary heatpumps and auxiliary power units that run on a variety of fuels. The DGII engine was derived from an existing model LOCR 407 diesel rotary engine which features a 407 cc displacement, low speed operation (3600 RPM), a liquid cooled housing, and an air cooled rotor. This engine was then extensively modified by DGII, in conjunction with Wankel, to meet the HFE program goals.

The modified engine is a turbocharged, liquid cooled single rotor Wankel rotary engine with a total displacement of 407 cc. The engine was modified as follows: (a) cooling of the rotor was changed from air cooling to oil cooling by the addition of a pressurized oil system, thereby overcoming the breathing and cooling problems found to exist with an air cooled rotor, (b) a special mechanical fuel pump cam and return spring were developed which eliminates tappet float at the high engine speeds (6000 RPM) required to produce 50 HP and ensure proper fuel injection characteristics, (c) the optimum injection spray angle into the combustion chamber was determined to promote proper air/fuel mixing (critical for igniting heavy fuels), (d) long lasting ceramic seals which extend seal life (engine life) 4 to 5 times that of standard iron seals were designed and installed, (e) a small exhaust gas driven turbocharger was installed onto the engine to increase power output while maintaining a small engine displacement (407 cc), and (f) a liquid to air intercooler between the turbocharger compressor outlet and the engine air intake was installed to increase the density of the intake air.

The engine was designed to have an operational speed range from 3000 to 6000 RPM and operate unthrottled, with the engine speed controlled by the quantity of fuel injected. Fuel injection timing and duration are controlled mechanically by the cam profile in the fuel pump and are not adjustable. The engine incorporates a turbine inlet cooling jacket on the turbocharger to maintain an upper limit on exhaust gas temperature into the turbine, resulting in increased turbocharger durability. Engine power output is controlled by varying the rack position on the fuel pump as the rack position determines the quantity of fuel injected. A summary of engine design characteristics are as follows:

Contractor Name:	DGII
Engine Manufacturer:	Wankel, GmbH
Engine Type:	Wankel Rotary
Configuration:	Single Rotor, Turbocharged
Combustion Type:	Single injector, spark assisted diesel
Combustion Chamber:	Standard Wankel
Displacement:	407 cc
Compression Ratio:	10.2:1
Direction of Rotation:	CCW viewed facing PTO shaft
Maximum Power Output:	56.0 HP at 5800 RPM
Overspeed Limit:	6500 RPM
Idle Speed:	3000 RPM
Fuel Consumption:	0.71 lb/HP-hr at maximum power 0.52 lb/HP-hr at cruise power
Engine Dry Weight:	102 lbs - Complete w/starter and turbo, w/o alternator and propeller
Ignition System:	Solid state 12 VDC
Starting System:	Integral 12 VDC Starter Motor
Fuel Inj. Pressure:	5000 psig
Fuel Inj. Pump:	Bosch, high pressure mechanical, model PFE 1Q 70/36 with 7.0 mm plunger dia., with eccentric cam profile
Fuel Injectors:	Bosch; 3x21 mm x 75°
Turbocharger:	IHI model RH65, medium boost pressure (12 psig), automotive type w/wastegate
Turbo Inlet Temp:	1710°F Maximum
Trochoid Housing Mtl:	Aluminum, Nickasil coating on trochoid surface

Rotor Material:	Iron Alloy
Cooling:	Liquid cooled engine housing (50/50 mix water/ethylene-glycol) Liquid cooled turbo jacket (50/50 mix water/ethylene-glycol) Oil Cooled Rotor Exhaust Pipe Cooling Jacket
Engine Coolant Temp:	210°F Maximum
Turbo Jacket Temp:	210°F Maximum
Intercooler Air Temp:	160°F Maximum
Lubrication:	Closed loop pressure feed system for engine and turbocharger bearings Oil metering pump for rotor seals
Lubricating Oil:	SAE 15W40 or SAE 30 or MIL-L-2104C for both oil systems
Lubricating Oil Temp:	260°F Maximum
Oil Capacity:	Sump: 3.69 quarts Metering Reservoir: 1.0 quart
Fuel:	JP-5, JP-8, and Diesel

2.1.3 SwRI

The engine delivered by SwRI was designed and manufactured by the Cuyuna Engine Company located in Crosby, Minnesota. Cuyuna has designed and manufacture a complete line of single and twin cylinder two-stroke engines, both liquid and air cooled, for ultra-light aircraft and small watercraft installations. The engine delivered for this test was designed to be fully optimized for UAV applications. Cuyuna designed and constructed the new engine and SwRI performed the combustion system and fuel system development for this engine and performed all development testing prior to delivery to NAVAIRWARCENACDIVTRN.

The engine is a naturally aspirated, spark ignition, reciprocating internal combustion engine designed to operate on heavy fuels (JP-5, JP-8, and Diesel) with an operational speed range between 2500 and 6000 RPM. The engine was designed to run unthrottled, with the engine speed controlled by the amount of fuel injected into the cylinders. The engine features two cylinders arranged in an inline configuration, is piston ported, and operates on a two-stroke cycle. A belt driven fuel injection pump is used to deliver fuel at 2800 psig to two fuel injectors, one located in the center of each cylinder head. The fuel injector in each cylinder head has a single orifice that directs the compressed fuel to impinge directly on a flat portion of the cylinder head, causing atomization.

In order to meet the HFE program 50 pound weight goal, the engine employs thin wall construction for the aluminum crankcase and cylinder castings and features a lightweight press fit crankshaft with a hollow main shaft and crank pins. Other significant engine design characteristics are as follows:

Contractor Name:	Southwest Research Institute
Engine Manufacturer:	Cuyuna Engine Co.
Engine Type:	2-Stroke, Reciprocating Piston
Configuration:	Twin Cylinder Inline, Naturally Aspirated
Combustion Type:	Stratified Charge
Combustion Chamber:	Trench head design w/direct impingement fuel injection
Displacement:	544.0 cc (33.2 cu.in.)
Bore:	73.0 mm (2.874 in.)
Stroke:	65.0 mm (2.559 in.)
Trapped Compression Ratio:	5.8:1
Direction of Rotation:	CCW viewed facing PTO shaft
Maximum Power Output:	35.3 HP @ 5000 RPM
Overspeed Limit:	6500 RPM
Idle Speed:	2000 RPM
Fuel Consumption:	0.69 lb/HP-hr at cruise power
Engine Dry Weight:	50.0 lbs w/o exhaust system
Ignition System:	MSD high energy capacitive discharge system model MC1

Spark Plugs:	NGK B7ES, 2 plugs per cylinder
Fuel Injection Pressure:	2800 psig
Fuel Injection Pump:	Bosch EP/ZEB-2KL
Fuel Injectors:	Bosch KBAL w/single 0.016 in. diameter orifice
Cylinder Material:	356 Aluminum alloy, sand cast, Chrome plated bores
Crankcase Material:	356 Aluminum alloy, sand cast,
Connecting Rods:	Steel forging w/needle bearings at lower and upper Ends
Crankshaft:	Steel forging, "T" type, hollow main shaft and crank pins, two single row and two double row ball bearings
Piston Rings:	Half-Keystone compression rings, two (2) per piston
Engine Cooling:	Crankshaft driven coolant pump, with circulation of 50/50 mixture of water/ethylene glycol thru crankcase, cylinders, and cylinder heads
Lubrication:	Crankshaft driven lube pump injecting oil only into cylinder inlet ports
Lubricating Oil:	Belray MC1 2-Cycle or equivalent
Fuel:	JP-5, JP-8, and Diesel Fuel

2.2 ENGINE INSTALLATION

2.2.1 AAI

The AAI engine was delivered to NAVAIRWARCENACDIVTRN on 1 April 1992 and was uncrated for inspection. No discrepancies were found and the engine was then installed in altitude chamber 6W. The engine was installed on a spider type engine mounting frame used to connect the engine to a 1.0 inch thick mounting plate which was in turn was connected to a torque reaction mount located on a stand in the test cell. The reaction mount was used to measure torque independent from the load cell mounted on the waterbrake load absorber. The engine output shaft was directly coupled via a flexible coupling (Lord mount) to a 200 horsepower Stuska model 400 load absorbing waterbrake. Figure 1 is a photograph of the AAI engine installed in the test cell 6W.

A computer controlled mission simulation program was developed which controlled output signals to various subsystems based on inputs. The inputs consisted of engine inlet pressure, engine inlet temperature, and exhaust pressure. The output signals consisted of inlet temperature, exhaust pressure, true airspeed and power lever voltage (PLV) setting. The inlet temperature output signal was sent as a set point to the controller on a portable air supply unit. The controller modulated the unit to maintain the desired temperature setting. The exhaust pressure setting was sent as a set point to the control valve on the cell exhauster unit. The control valve modulated exhaust airflow to maintain the desired cell pressure. The true air speed signal was sent as an input to the automatic propeller load curve equation for use in calculating the correct propeller load. The PLV set point signal was sent to the PLV controller to command changes in engine power output as required.

The waterbrake controller was capable of operation in speed governing mode, torque governing mode, and automatic propeller load simulation mode. A 386 IBM compatible computer was programmed to read inputs of engine inlet pressure, temperature, engine speed, and air velocity and then output a desired torque set point. The torque set point was sent to the Digalog dynamometer controller which provided modulating signals to the waterbrake water inlet valve. A load cell on the waterbrake measured actual torque and provided the Digalog controller with a feedback signal for fine tuning the valve modulating signal. The load cell was calibrated in the range of 0 to 60 lb-ft. The propeller load curve which we selected for this test matched the propeller load curve of the 2-bladed wooden propeller which AAI had run on the engine during their development testing.

The engine power setting was controlled by sending a 0 to 5 VDC command signal to the ECU. The 0 to 5 volt speed signal corresponded to 3000 (idle) and 6800 (wide open throttle (WOT)) RPM, respectively.

Engine cooling consisted of a water/glycol mixture being circulated by the engine's integral water pump through a liquid to liquid heat exchanger mounted in the test cell. A thermostat in the engine housing regulated the flow of engine coolant to maintain a coolant temperature of 190°F. The heat exchanger temperature was controlled by regulating the facility cooling tower water allowed to enter the liquid to liquid heat exchanger.

Engine exhaust gases were ducted from the test cell through the 6W exhaust header. A combination of facility blowers and exhausters in combination with a temperature control system were used to simulate desired altitude conditions in the test cell. A sea level exhaust bleed valve was opened when the engine was being tested at sea level conditions.

Engine starting was accomplished with an Ingersoll-Rand model SS175G air starter which engaged a drive on the anti-engine end of the waterbrake. Shop air supply pressure was regulated to control the air starter speed.

JP-5 fuel was used for all testing. Fuel supply pressure to the fuel pump was set in the range of 15 to 25 psig. Oil used for bearing and apex seal lubrication during the test was Golden Spectro brand synthetic two-stroke oil.

2.2.2 DGII

The DGII engine was delivered to NAVAIRWARCENACDIVTRN on 20 July 1992. The engine was uncrated for inspection and it was found that the incorrect turbocharger had been installed on the engine. Discussion with DGII indicated that the final turbocharger version was not available in time for our testing. The engine was installed in test cell 6W as described above in section 2.2.1 with the following differences: additional heat exchanger systems for the engine housing cooling, pressurized oil system, turbocharger cooling jacket, and the exhaust pipe cooling jacket were installed and a 3.69 quart oil reservoir tank to accommodate the pressurized engine oil delivery system was mounted in the cell. For this engine test, the propeller load curve input into the computer was designed to absorb 50 HP at 6000 RPM at an airspeed of 70 knots. We also had the options of running the engine in speed governing mode and manual load control mode. Figures 2a and 2b show the test cell configuration and engine installation in test cell 6W.

The temperatures of the liquid coolant for the engine housing, engine oil, turbine inlet air (engine exhaust gas temperature), turbocharger cooling jacket and charger air intake (through compressor intercooler) were maintained by independent heat exchanger systems. Temperatures of these systems were controlled by either thermostatic, electric and/or manual valves.

Ignition was accomplished with a high energy ignition coil and spark plug system which was triggered by a Hall speed sensor located on the engine.

JP-5 fuel was used for all testing. Fuel supply pressure to the fuel injection pump was regulated to 3.0 to 5.0 psig. Engine lubrication oil was Valvoline SAE 15W40.

2.2.3 SwRI

The 550 cc engine arrived at NAVAIRWARCENACDIVTRN on 23 April 1992 and was uncrated for inspection. No discrepancies were found and the engine was mounted on a steel table fabricated by SwRI and used exclusively for all their development testing. Also mounted on the table were a Froude AG-80 eddy current dynamometer, a Delco Remy model 50 MT 12 volt electric starter motor, and a Horton air clutch connecting the starter to the dynamometer. The dynamometer was connected to a Spicer 1310 series slip yoke driveshaft featuring two universal joints, one on each end of the splined shaft. The universal joints allowed for engine to dynamometer deflections up to 15° in any direction at speeds up to 6000 RPM. An adapter was used to connect the Spicer driveshaft to the 10:1 tapered power take-off (PTO) shaft of the engine. After a complete inspection, the engine, table, and table components were delivered to ATA where they were installed in the test area designated B-Room. Figures 3 and 4 show the engine installed on the supplied table in B-Room.

The engine was soft mounted to the table with an elastomer bushing/stud/nut combination located between the table mount and the steel adapter bars bolted to the crankcase of the engine. The mounting frame was in turn welded to the table and the table was then bolted to the bed plate in B-Room.

Horsepower absorption was accomplished with the Froude AG-80 eddy current dynamometer loaned to us by SwRI for the duration of our testing. This dynamometer, being liquid cooled, was plumbed into the existing dynamometer coolant loop already in B-Room which can be seen in Figure 5. The reasoning for using this particular dynamometer was that, compared to other eddy current dynamometers, the Froude AG-80 has a very low moment of inertia (i.e., 93.7 lb-in^2) which we required to accurately simulate a 50 HP fixed pitch flight propeller loading. The load cell supplied with the dynamometer to measure engine torque was calibrated by NAVAIRWARCENACDIVTRN personnel and used for the entirety of this test.

The engine power was set with two manual vernier cables which controlled airflow (via two engine mounted throttle bodies) and fuel flow (via the engine fuel pump rack position). The cables featured both coarse and fine adjustments and could be locked in place from the control room. During later stages of testing, fuel flow was controlled by an electric linear actuator with an analog position control, as cable slack and engine vibrations caused poor repeatability with the vernier cable.

Fuel injection pump to engine phasing (timing) was controlled by a Candy Co. Dynamic Differential Drive unit (model DO1A) mounted to the crankshaft at the rear of the engine, with the differential output shaft driving the fuel injection pump via a cogged belt. The Candy differential was controlled by a bi-directional servomotor from the control room which allowed adjustment of ± 360° from piston top dead center (TDC) position. This arrangement allowed injection timing to be changed while the engine was running, allowing us to observe any changes to engine performance. Both the Candy differential unit and the electric servomotor can be seen in Figure 6, a rear view of the engine installation.

Engine cooling consisted of water being circulated by the engine's integral water pump (driven directly by a worm gear from the engine crankshaft) through a liquid to liquid heat exchanger mounted on the engine table. The heat exchanger was connected to an existing water/ethylene glycol system designed for a larger dynamometer also located in B-Room which has an integral coolant reservoir and pump. The system also featured an adjustable thermostatic valve which was set to 190°F for this test.

Engine exhaust gases were ducted from the expansion chamber via a 6.0 inch diameter flexible stainless steel pipe to a Dayton 120 volt centrifugal blower.

Engine starts were accomplished with a Delco Remy model 50 MT 12 volt electric starter motor mounted directly to the table. A Horton air clutch was used to engage and disengage the starter when desired. An adjustable time-delay relay allowed 60 psig of facility shop air to engage the clutch three seconds after the engine-run key (located in the control room) was turned to the "start" position.

Fuel used during testing was limited to JP-5. Originally, we planned to begin testing with JP-5 and then switch to JP-8 and Diesel for the remainder of the program. Because the 10:1 tapered output shaft coupling slipped on the engine PTO shaft, the engine performance was seriously degraded and we decided not to switch fuels until the problem was identified. The output shaft coupling slippage precluded operation with JP-8 and Diesel fuels. It should be noted that SwRI tested the engine exclusively with JP-8 fuel and the engine performance demonstrated by SwRI was with JP-8. Fuel supply pressure to the fuel injection pump was in the range of 4 to 10 psig as recommended by SwRI for the duration of the test. Engine oil used during the test was Belray MC1+ synthetic oil designed specifically for high performance two-stroke engines. Lubricating oil used in the Candy Co. differential was SAE 90 gear lubricant.

2.3 INSTRUMENTATION

2.3.1 AAI

The AAI engine test instrumentation was installed as defined in Appendix A.

2.3.1.1 MEASURANDS

Engine speed was measured with a Hall-type magnetic sensor and a trigger wheel attached to the end of the engine power take-off shaft. Waterbrake speed was also measured in a similar manner. Automatic engine overspeed protection was provided by shutting off the 12 VDC power supply to the ECU and the fuel injector solenoid valves when an engine overspeed occurred.

Engine torque was measured by two independent methods for this test. The engine was directly mounted on a torque reaction mount which measured torque at the engine with a calibrated load cell. This reaction mount could be locked in place when not required. The second torque measuring device was a calibrated load cell mounted to an arm of the waterbrake. Both load cells were calibrated at NAVAIRWARCENACDIVTRN prior to the test to ensure their acceptable accuracy.

Fuel pressure supplied to the injectors was measured with NAVAIRWARCENACDIVTRN pressure transducers.

Fuel injection timing and duration was controlled by the ECU. Because the injection timing used rotor TDC position as a reference point, the ECU continuously sensed TDC position via a magnetic sensor attached to the engine crankshaft.

2.3.1.2 DATA ACQUISITION

a. BASIC SYSTEM

Engine performance parameters were acquired in both steady-state and transient modes by the NAVAIRWARCENACDIVTRN Data Acquisition System, recorded and processed by a PDP 11/84 computer on-line and a VAX 11-780 off-line. Transient data were acquired at a rate of 100 samples per second and a failure monitor tape, which acquired data at 50 samples per second, continuously recorded the previous five minutes of testing.

The on-line computer system used a computer program to calculate and provide desired engine data in both real time and steady-state modes. Selected performance parameters were displayed in the control room of the test cell via cathode ray tube monitors and dedicated gauges for real time monitoring and analysis. In addition, parameters from engine monitoring instrumentation were recorded manually on log sheets by test cell personnel during engine operation.

b. STEADY STATE PRESSURE SYSTEM

Steady state pressures were acquired through a pressure scanning system manufactured by Scanivalve, Inc. The system consists of several modules, each of which contains a pressure transducer. Each module switches up to 48 pneumatic pressure inputs to the single transducer. Two or three inputs to each module are reserved for known calibrated pressures. These allow the stored multipoint curve fits of the transducer characteristics to be modified at run time for any slight changes that may have occurred. This system acquires pressures at a rate of approximately two pressures per module per second.

c. TRANSIENT PRESSURE SYSTEM

Transient pressures were measured using individual transducers conditioned by an amplifier-multiplexer-digitizer unit.

d. TEMPERATURE MEASUREMENT SYSTEM

Steady state and transient temperatures were measured using thermocouples made of chromal-constantan (type E) and chromal-alumel (type K). The thermocouples were referenced to Universal Test Reference (UTR) units mounted remotely from the engine. The UTR is a mass of aluminum that is insulated to control its temperature. No attempt is made to control the reference temperature. Instead, the temperature is measured with an accurate independent device.

e. VIBRATION MEASUREMENT

Engine vibrations and waterbrake vibrations were measured with Endevco accelerometers. The vibrations measured by the accelerometers were displayed in the control room on root mean square (RMS) averaging meters and recorded during both steady state and transient data acquisition periods.

2.3.1.3 INSTRUMENTATION ACCURACY

The accuracies of the NAVAIRWARCENACDIVTRN instrumentation systems are presented in Appendix B.

2.3.2 DGII

The DGII engine test instrumentation was installed as defined in Appendix C.

2.3.2.1 MEASURANDS

The amount of fuel delivered to the engine was controlled by a NAVAIRWARCENACDIVTRN servomotor, which determined the rack position on the engine fuel injection system. A feedback signal from the servomotor validated the actual fuel injection pump rack position.

Automatic engine overspeed protection was provided in the PLV circuit. If the engine speed exceeded 6500 RPM a trip switch would send an independent command to the fuel injection pump servomotor for a full stop.

2.3.2.2 DATA ACQUISITION

The data acquisition system used for the DGII engine test was the same as described in section 2.3.1.2.

2.3.2.3 INSTRUMENTATION ACCURACY

The accuracies of the NAVAIRWARCENACDIVTRN instrumentation systems are presented in Appendix B.

2.3.3 SwRI

The SwRI engine test instrumentation was installed as defined in Appendix D.

2.3.3.1 MEASURANDS

Dynamometer speed (equal to engine speed) was measured from a Hall type sensor integral to the Froude dynamometer and read in the control room on the dynamometer controller display.

Peak cylinder pressure was measured for one cylinder with a Kistler model 6004 pressure transducer mounted directly in the cylinder head. The signal from the transducer was fed to a Kistler model 5004 Charge Amplifier and then routed to a digital storage oscilloscope located in the control room.

Fuel injector timing and duration were measured with an instrumented Bosch fuel injector. The signal was feed to a Wolff Controls Co. charge amplifier and then to the digital storage oscilloscope located in the control room.

Ignition timing was measured using an induction coil wrapped around one of the ignition system's trigger wires at the coil. This signal was fed to the digital storage oscilloscope located in the control room.

Piston TDC positioning was indicated using three trigger pegs mounted on the engine output shaft adapter mount which passed by a hall sensor mounted on the driveshaft scattershield. The hall sensor signal was transmitted to the digital storage oscilloscope located in the control room.

Engine airflow was measured using a Meriam Instrument Co. model 50MC2-4F Laminar Flow Element connected in series to a 55 gallon container which functioned as a plenum chamber to smooth out the pulsating flow inherent to intermittent combustion engines.

2.3.3.2 DATA ACQUISITION

The data acquisition system used in ATA B-Room consisted of a Digilog PC system. This system was capable of acquiring steady state data at a rate of one sample (of all inputs) per second. The Digilog was capable of performing simple mathematical functions (addition, subtraction, division, and multiplication) and was also capable of providing analog outputs for use in controlling external hardware.

Steady state pressures were measured with individual transducers conditioned with a PPM Model SG-16-3 signal conditioning system before being recorded on the Digilog system.

Steady state temperatures were measured as stated in section 2.3.1.2.d.

2.3.3.3 INSTRUMENTATION ACCURACY

The accuracies of the NAVAIRWARCENACDIVTRN instrumentation used for this test were as follows:

Instrument Description	Accuracy
TYPE E THERMOCOUPLE	+/- 2°F
TYPE K THERMOCOUPLE	+/- 4°F
PRESSURE TRANSDUCER	+/- 1%
FUEL FLOWMETER	+/- 2%

LOAD CELL (TORQUE)	+/- 1%

3.0 METHOD OF TEST

3.1 PLANNED

The HFE test program planned for all three engines consisted of engine calibrations and mission simulations in atmospheres based on MIL-STD-210, with the following modifications: We increased the maximum high temperature from 103°F to 125°, and we increased the minimum low temperature from -60°F to -25°F. This is consistent with UAV requirements as defined in the UAV Master Plan. The specific test plan planned for the three HFE engines was as follows:

a. Performance Mapping Calibrations throughout the entire engine operational RPM range in 500 RPM increments, at altitudes from Sea Level to 15,000 ft using JP-5, JP-8 and Diesel fuels;

b. Sea Level starting tests at MIL-STD-210 Hot, Cold, and Standard Day conditions using JP-5, JP-8, and Diesel fuels;

c. MIL-STD-210 Hot, Cold, and Standard Day Operational testing and Training Mission simulations using JP-5, JP-8, and Diesel fuels.

The purpose of the engine calibrations was to determine engine power output at constant speeds while varying PLV (i.e., engine load).

The purpose of the operational missions was to verify proper engine operation with the three heavy fuels (JP-5, JP-8, and Diesel) at various conditions with a typical UAV mission flight profile. The three operational missions chosen were a Hot Day (MIL-STD-210) mission with JP-8 fuel, a Cold Day (MIL-STD-210) mission with JP-5 fuel and Standard Day (MIL-STD-210) mission with diesel fuel. The three missions are shown in Tables 1,2, and 3.

The engine start tests were to be conducted after a one hour soak at the given conditions prior to the start of each above mentioned operational mission.

The purpose of the training missions was to simulate the typical flying performed with current UAVs using all three heavy fuels at Standard Day conditions. Each of the three missions were to be repeated 15 times to demonstrate acceptable engine speed/power transients. The training missions are listed in Table 4.

3.2 TEST CONDUCT

3.2.1 AAI

Because our original test plan was not compatible with the operation of the engine ECU, testing of the AAI engine was divided into two phases. In Phase I the ECU maintained a constant engine RPM while we varied engine output via waterbrake loading. During Phase II, AAI modified the ECU to control the engine by varying engine RPM to provide a desired torque. This modification allowed us to continue testing with our original test plan. Figure 7 is a graph with the planned test data points and the propeller load curve, which was tailored to match the predicted engine output. Appendices E and F are a chronology of events from both Phase I and Phase II of the test, respectively.

3.2.2 DGII

Due to unexpectedly high engine output at increasing altitude conditions, instability at low power output, and finally an engine failure, the actual test did not proceed as planned. The engine power output did not lapse at as quickly a rate as a naturally aspirated engine and we determined that our sea level throttle operating settings were not sufficient for altitude operation. To accurately determine these settings, a more detailed calibration at each of the altitude conditions was required. Data acquired from the calibrations was used in combination with the desired propeller load curves to establish points of intersection of engine load, engine speed, and vehicle flight condition. Once a complete mapping of engine power versus engine speed at various rack (PLV) positions was determined, the desired propeller load curve was overlaid on top of the data. The intersection of the desired load curves with the calibration data determined which rack (PLV) positions would provide the desired combination of engine power and speed. The PLV positions acquired from the calibrations were essential information for use as input to the operational missions. The planned calibration conditions are provided in Table 5.

We began with a sea level calibration followed by a 15K ft calibration with the intent of continuing our calibrations at 5K ft and 10K ft. Following the completion of each calibration we explored the transient response of the engine through a series of bodies (idle to maximum to idle). On our approach from sea level to 15K ft altitude (the next calibration condition), we conducted a series of successful engine starts at 7500 ft altitude. By the time we approached the end of the second calibration (15K ft), the total accumulated engine time was 33.38 hours including 7 hours of DGII/Wankel test time. Before we were able to acquire the low speed, high power points, the engine seized. The test was declared discontinued until further notice.

3.2.3 SwRI

The delivered engine did not have the engine porting, exhaust system, or fuel system fully optimized. For these reasons the engine delivered to us was not at a state of development to warrant the planned testing listed above in section 3.1.

In an effort to evaluate the engine in its "as delivered" state of development, we decided to forgo installing the engine in an altitude test cell and instead installed the engine in a sea level test area where we could determine its operability and continue the development of the engine. By eliminating operation at altitude conditions, the sea level test area could be operated at a substantially lower cost.

The testing was performed at sea level and ambient day conditions at NAVAIRWARCENACDIVTRN during the months of June through December. The actual testing performed on the SwRI engine was as follows:

3.2.3.1 BASELINE ENGINE PERFORMANCE

The first objective of testing was to determine the baseline engine performance from 3000 to 6000 RPM in the configuration delivered to us from SwRI. The engine was started normally at a dynamometer control setting of 4500 RPM in order to eliminate any dynamometer excitation, as the starter motor was capable of maintaining 3000 RPM cranking speeds during start. Once running, the engine was allowed to reach operating temperature (190°F) before adjustments were made to the throttle and fuel rack position. The throttle and fuel rack position were then varied to produce maximum power and/or best BSFC at that condition. Once maximum power and/or best BSFC was established, injection timing and spark timing were varied to determine the best values at that condition. Data was taken over the entire speed range, although particular attention was paid to the 4000 to 5500 RPM range as this was perceived as an acceptable cruise speed range.

3.2.3.2 EXHAUST SYSTEM TUNING

Four different exhaust systems were investigated in order to improve power output and lower BSFC established during baseline testing. Baseline performance was acquired with a single 570 cc exhaust pipe, as recommended by SwRI. The exhaust systems investigated were as follows:

1. Dual 570 cc Yamaha Exciter exhaust,

2. Modified single 570 cc Yamaha Exciter exhaust,

3. Single 560 cc Arctic Cat exhaust,

4. Dual 560 cc Arctic Cat exhaust.

Each exhaust system was installed and the engine was run as described above in 3.2.3.1.

3.2.3.3 TURBOCHARGER TESTING

To increase maximum engine power and lower BSFC, it was decided to investigate the installation of an exhaust driven turbocharger. Simulated turbocharger testing by SwRI indicated that an increase in power output from modest levels (less than 5 psi) of turbocharger boost pressure were possible. A Warner Ishi model RBH53, which can be seen in Figure 8, was sized for the engine and procured for testing. The turbocharger was installed on the engine test stand and connected to a separate oil lubrication system. The turbocharger weighed less than 10 pounds, featured an integral wastegate and oil cooled bearings for durability. Test methodology for this phase of testing was the same as described in 3.2.3.1.

3.3 DATA REDUCTION

3.3.1 AAI

The engine steady state performance was calculated using the equations in Appendix G.

3.3.2 DGII

The engine steady state performance was calculated using the equations in Appendix H.

3.3.3 SwRI

The engine steady state performance was calculated using the equations in Appendix I.

4.0 ANALYSIS OF TEST DATA & DISCUSSION

4.1 PERFORMANCE

4.1.1 AAI

4.1.1.1 ENGINE COMPRESSION

Two AAI engines, serial numbers (S/N) 0101 and 0102, featuring two different compression ratios, were used during testing. Table 6 shows the dates each engine was installed in the test cell, the engine serial number, engine build number, and the compression ratio of the engine.

The engines tested with the 8.8:1 compression ratio rotor installed exhibited poor operability compared to the 8.0:1 compression ratio rotor engine. All the data discussed in this report were obtained with the 8.0:1 compression ratio engine.

During testing, we conducted leakdown tests to check the condition of the rotor apex seals and springs. These tests were conducted by pumping 60.0 psig air into the combustion chamber while holding the rotor fixed at the TDC position. We measured the pressure drop across a 0.060 inch orifice upstream of the combustion chamber. The measured pressure drop with new apex seals and springs installed was 10.0 psig or less. The pressure drop notably increased when the seals and springs were damaged. The engine was considered unacceptable when the pressure drop was 40.0 psig or greater.

4.1.1.2 STARTABILITY

Throughout the test, many engine starts were attempted. When all of the engine components were working properly, the engine started satisfactorily. The engine was able to successfully start at 7500 ft ambient pressure conditions.

4.1.1.3 CALIBRATION PERFORMANCE

Calibrations were conducted at sea level Standard Day conditions with JP-5 fuel. During engine calibrations, the dynamometer was operated in a speed governing mode. While holding the engine at constant speed, data were recorded at various throttle positions. Because the engine ECU did not allow adjustments in 500 RPM increments (please refer to section 4.2.1.1. for more detail), we modified the test plan and recorded data at speeds where the engine operation was stable. Figures 9 and 10 show engine calibration data plotted on a graph with the sea level propeller load curve.

4.1.1.4 SIMULATED PROPELLER OPERATION

Based upon AAI supplied information that the engine could produce 43 HP @ 6800 on a propeller load curve, we programmed our waterbrake controller to automatically simulate propeller load as a function of RPM. Figure 11 shows the propeller load curve at sea level at 0 knots and 70 knots true airspeed. Actual engine inlet temperature and pressure were used to generate the propeller load curve. Thus, the load curve was automatically adjusted for any altitude condition. In addition, a multiplication factor was added to the load equation to increase or decrease the load as desired. Small differences between the recorded data and the propeller load curve can be attributed to differences in temperature and pressure from sea level Standard Day conditions.

Although the control system loaded the engine at or near the desired load condition, the engine did overspeed several times, causing the power to the high speed solenoid valves to be automatically cut off to stop the engine. The overspeed condition typically occurred while advancing the PLV as engine speed did not respond linearly to increases in PLV as expected. Typically, while advancing the PLV, the RPM would remain constant to a point and then rapidly increase until the overspeed limit was reached, causing an overspeed shut down. This rapid acceleration exceeded the waterbrake response time. Figure 12 shows a transient plot of the engine response to PLV advance resulting in an engine overspeed shutdown.

Figures 13 through 15 show steady state data of engine operation on a propeller load curve. Each figure shows BSFC data corresponding to the propeller load data points. In the plots where BSFC data is not shown, the inlet fuel flow meter was malfunctioning at the time the data was recorded and the data has been judged to be inaccurate. Figure 13 shows the highest power point recorded at 32 HP and 5900 RPM with a BSFC of 0.42 lb/HP-hr. Figure 15 shows a transient plot of the engine operating on the propeller load curve at the time the 32 HP data point was recorded. Altitude data were recorded and are shown in Figure 14.

4.1.1.5 TURBOCHARGER PERFORMANCE

The turbocharger installed on the AAI HFE has variable inlet guide vanes designed to hold a constant boost pressure of one atmosphere above ambient pressure throughout the engine operational speed range. The inlet guide vanes are mechanically controlled by a shaft attached to a pressure sensing diaphragm. Figure 16 is a plot of engine manifold inlet pressure (MAP) at sea level that indicates a turbocharger boost pressure of one atmosphere (59.84 in HgA) was not maintained over the operating speed range of the engine. Figure 17 shows transient plots of MAP and turbine inlet temperature during a PLV increase.

4.1.2 DGII

4.1.2.1 CALIBRATION PERFORMANCE

Calibrations were conducted at both sea level and 15K ft Standard Day conditions with JP-5 fuel with the dynamometer in speed governing mode. At each specific speed, a series of data points were gathered at specific throttle positions. The minimum stable output obtained during the calibrations occurred at 6.5 ft-lbs at 4000 RPM.

Figure 18 shows the sea level, Standard Day power curve and Figure 19 shows the sea level, Standard Day BSFC curve. It is important to note that at WOT, peak power occurred at approximately 5800 RPM. At WOT and 5800 RPM, peak power was 56.0 HP and BSFC was 0.71 lb/HP-hr. At the cruise condition (85 percent PLV and 5000 RPM), the BSFC was 0.52 lb/HP-hr and the power available was 37.0 HP. Engine operation became unstable below 4000 RPM and therefore steady state data were unobtainable. The BSFC data show a general trend of improving BSFC with increasing engine power output. This was true from 65 to 95 percent PLV in the speed range of 4000 to 5400 RPM respectively. BSFC performance from 95 to 100 percent PLV decreased in the speed range from 4000 to 5400 RPM. At speeds above 5400 RPM, the trend of improving BSFC with increasing PLV was exhibited from 65 to 80 percent. PLV openings above 80 percent result in BSFC performance losses. Figure 20 shows an overlay of the simulated propeller load curve and the calibration data. Intersection points indicate the engine output power and speed combinations which will be produced with a given propeller load curve and PLV setting at a specific flight condition.

Operation at 15K ft Standard Day conditions revealed that peak power at WOT was 44.0 HP and occurred at 5600 RPM. The BSFC at this point was 0.78 lb/HP-hr. At a cruise condition (85 percent PLV and 5000 RPM) the BSFC was 0.67 lb/HP-hr and the power available was 31.0 HP. These data are shown in Figures 21 and 22, respectively. The BSFC data shows a general trend of improving BSFC with increasing engine power output. This is true from 65 percent to 85 percent PLV in the entire speed range. BSFC performance from 85 to 100 PLV decreases in this range. We were unable to maintain stable engine operation below 4200 RPM until we increased PLV to 95 percent and above. Figure 23 shows an overlay of the simulated propeller load curve and the calibration data.

Figure 24 shows engine manifold pressure versus power for calibration data obtained at sea level and 15K ft conditions. The turbocharger provided up to 47.6 in Hg boost pressure at sea level and 30.0 in Hg boost pressure at 15K ft. Notice that the engine could provide a constant power output in a wide band of manifold pressures (13.0 in Hg Differential). This is true up to 44.0 HP. This identifies the good possibility of using wastegate control to deliver lower loads at lower manifold pressures which would result in lower air to fuel ratios and more stable low end operation. Negative aspects of engine operability include not being able to maintain engine operation below 6.0 HP at either condition and not being able to operate the engine below 4000 RPM at any load. This points toward a fuel delivery system problem which is related to low speed operation and/or a poor combustion/atomization process at low speed operation.

4.1.2.2 SIMULATED PROPELLER OPERATION PERFORMANCE

The dynamometer was switched to automatic propeller load control mode in order to evaluate engine steady state and transient operation. The steady state data, presented in Figure 25, show the power and BSFC obtained while operating on the simulated propeller load curve. Stable operation at low load was limited to 20.0 ft-lbs on the 70 kt propeller load curve due to a low speed/load engine instability. We were unable to transition to speeds below 4500 RPM while under propeller load simulation control. Transient response to PLV input commands was also monitored. A series of PLV transients were conducted to evaluate engine response to quick accelerations, decelerations, and bodies. Results from this information were to be used as throttle ramp inputs to our automatic mission control program.

Figures 26a and 26b show a typical snap bodie on a 70 kt sea level propeller load curve. The engine responded very quickly and accurately to the snap acceleration command and achieved maximum power output within 3 seconds of the command with engine stabilization achieved within 5 seconds of the command. Speed fluctuations were minimal (+/- 50 rpm). The engine responded quickly to the snap deceleration command and achieved idle power within 5 seconds. Stability at idle was achieved within 20 seconds of the deceleration command.

Figures 27a and 27b show a typical snap bodie on the 0 kt sea level propeller load curve. The 0 kt load curve places a greater load on the engine than the 70 kt curve at any given engine speed causing the engine to reach maximum power output at a slightly lower speed, experience lower speed fluctuations at maximum power and greater stability problems at low power output. The engine responded very quickly to the acceleration command and achieved maximum power within 5 seconds with engine stabilization being achieved immediately. As the desired torque command and measured torque values merged together, engine output power gradually increased by 2.0 hp over a 12 second time interval with minimal speed fluctuations (+/- 25 rpm). The engine responded quickly to the deceleration command, but did not reach a stable idle power and speed. An increase in fuel injection quantity was commanded in order to prevent an engine stall.

While transitioning from sea level to 15K ft on the propeller load curve, we conducted two successful engine starts at a simulated altitude of 7500 ft. Figures 28a and 28b show the altitude, engine speed, output power, and time to start the engine at this condition. The engine reached a stabilized power level within 25 seconds during both starts. Speed fluctuations after the start were less than +/- 150 RPM. Output power fluctuations were caused by engine speed fluctuations. Because the speed fluctuations were used as inputs to the simulated propeller load controller, as speed changes occurred, the program adjusted the absorbed load.

4.1.2.3 OIL ANALYSIS

DGII recommended an oil change interval of 150 hours. To be conservative, we elected to service the oil in periods of 20 to 25 hours. During the course of the test, oil was drained and replaced twice. At the conclusion of the test the oil was drained. Samples were taken and analyzed for chemical properties. The results of the analyses are given in Table 7. Sample number 851 was a baseline sample provided for comparison. Sample number 836 accumulated 20.47 hours of use and appeared to have similar amounts of the specified chemical elements. Sample number 830 represents 5.20 hours of use and showed elevated levels of iron and aluminum. This indicates slight wear of the rotor seals and trochoid housing. Sample number 831 was taken at the conclusion of the engine test and accumulated only 0.77 hours of use. This sample also contained elevated levels of iron and aluminum.

4.1.3 SwRI

4.1.3.1 BASELINE PERFORMANCE

Figure 29 is a composite plot of SwRI claimed baseline performance for the engine as delivered. The engine was in a naturally aspirated configuration with the 570 cc exhaust system installed. The required propeller load can be met up to approximately 5300 RPM with BSFCs in the range of 0.55 to 0.7 lb/HP-hr. Cruise power (5000-5500 RPM) BSFCs were in the range of 0.57 to 0.65 lb/HP-hr. WOT performance showed a substantial increase in BSFC at all speeds, indicating poor air management in the combustion chamber during full load conditions. SwRI informed us that unthrottled operation was possible when running on the propeller curve from 3500 to 6000 RPM with the need to reduce airflow (with the engine installed throttle bodies) at slow speed settings (less than 3000 RPM) in order to avoid running the engine at fuel to air ratios (F/A) below the lean limit.

Figure 30 is a composite plot of the actual baseline performance obtained during our testing. The engine was run as delivered, naturally aspirated with the 570 cc exhaust system. It should be noted that the engine would not run unthrottled at any engine speed, although similar power and BSFC performance was consistent with that obtained by SwRI. Comparing Figure 30 to Figure 29, it is important to note that Figure 29 BSFC curves are averages over the RPM range, while Figure 30 contains acquired data points in a non-linear trend. The general shape of the WOT curve indicates the engine exhaust system was not functioning properly for maximum power at 6000 RPM.

4.1.3.2 MODIFIED 570 cc EXHAUST

In an attempt to reduce the tendency for unburnt fuel to collect and burn at the rear section of the exhaust pipe, the 570 cc exhaust pipe was modified. The modification entailed removal of the rear chamber walls that housed the expansion chamber's divergent cone section, thus precluding unburnt fuel from collecting and burning. Although this modification stopped fuel from collecting at the rear section of the pipe, the modified exhaust produced higher BSFCs at all RPMs relative to the unmodifed 570 cc exhaust system. This is clearly shown in Figure 31, where the BSFC of both the modified and unmodifed 570 cc exhaust system is plotted versus RPM. The increase in BSFC indicates that engine airflow was maintained but that the timing of the reverberation pulse in the exhaust pipe had been altered.

4.1.3.3 DUAL 570 cc EXHAUST

Engine operability using two 570 cc exhaust pipes was characterized by repeated stalling during adjustment of the fuel and air controls. This increased sensitivity to fuel/air ratio made the engine very difficult to control. Repeated stalling and the inability of the engine to reach operating temperature indicated poor combustion as compared to the single 570 cc pipe. In this configuration the exhaust system failed to properly scavenge, allowing the fresh fuel/air charge to escape into the exhaust system during blowdown. Once this occurred, there was a minimal amount of fresh fuel/air mixture that remained in the combustion chamber, making starting extremely difficult.

4.1.3.4 SINGLE 560 cc EXHAUST

A single exhaust system from an Arctic Cat 560 cc snowmobile engine was connected to a "Y" shaped adapter pipe that connected both engine exhaust ports to the single exhaust pipe. This was the same adapter used with the single 570 cc exhaust system. The engine could be started and produced a maximum of 21 hp at 4500 RPM with this exhaust configuration. No increase in power was experienced from 4500 to 6000 RPM, indicating the engine was airflow limited by this exhaust. This indicates the reverberation pulse produced in the exhaust system was timed too early relative to exhaust blowdown, thus limiting airflow and power.

4.1.3.5 DUAL 560 cc EXHAUST

Following the previously discussed attempt at using the single 560 cc exhaust/"Y" pipe configuration, a single 560 cc exhaust pipe was connected to each exhaust port. The engine could be started for brief moments, but would not produce any appreciable power and repeatedly fouled spark plugs. As with the dual 570 cc exhaust system, the dual 560 cc exhaust system adversely effected scavenging to the point where due to the lack of available air in the combustion chamber, the F/A ratio was extremely rich.

4.1.3.6 GENERAL DISCUSSION

The engine, as delivered by SwRI, does not operate on or near a true diesel (compression ignition) cycle. Due to the degree of fuel injection timing (120° advanced relative to TDC) the engine operates with a near homogeneous charge and may be considered a low compression ratio (5.8:1 trapped) "stratified charge" system.

The proper exhaust system is critical for any two-stroke engine to optimize airflow through the engine and produce maximum horsepower. Installation of an incorrectly tuned pipe can decrease the engine output by as much as 30%. Obviously, to realize the true potential of this engine, the proper tuned pipe exhaust system must be determined.

The engine would not run unthrottled at any speed during our testing, although SwRI stated the engine would run unthrottled at speeds from 3500 to 6000 RPM. Some throttling was required at all times, but airflow had to be drastically reduced at low speed settings to meet propeller load power. The reason for this phenomenon was not determined and should be investigated during future testing.

Despite problems with prototype cylinder head durability, the core engine (crankcase, crankshaft, crankshaft and connecting rod bearings, connecting rods, engine crankshaft seals, oil pump, water pump, and engine cylinders) can be considered durable, as no problems or failures were encountered with these components despite over 100 hours of extensive testing at SwRI and 14 hours of testing at NAVAIRWARCENACDIVTRN.

The 10:1 tapered output shaft (used exclusively by the snowmobile industry) proved unreliable, as slipping of the coupling on the shaft caused errors in the ignition and fuel injection timing of the engine.

The cylinder heads, being made entirely of aluminum, could not tolerate the repeated insertion and removal of the spark plugs and fuel injectors necessary during development testing. For development, the cylinder heads should have been made with stainless steel inserts for the spark plug threads and the fuel injector hold down bosses. Stainless steel should not be used for the entire cylinder head, as the heat transfer rate of stainless steel is substantially less than that of aluminum.

The fuel pump is very sensitive to rack movement as a small displacement of the rack provides a large increase in fuel flow. Because of this and the rack's susceptibility to vibrations, a mechanism should be devised to reduce the rack's sensitivity. Also, the fuel pump should be mounted in a manner to reduce or eliminate engine induced vibration. This will allow smoother operation by reducing the fluctuating RPM change caused by the rack control vibrating.

The engine is not overly sensitive to ignition timing. This is due to the multiple spark nature of the ignition system in which the spark plug is fired repeatedly during the combustion event.

Injection timing was also not as critical as expected. The engine operated satisfactorily with the injection timing set between 110 and 130 degrees advanced relative to TDC. This is due to the almost homogeneous nature of the fuel/air mixture.

4.2 ANOMALIES

4.2.1 AAI

4.2.1.1 ENGINE OVERSPEED

During testing we were not able to operate the engine at steady state conditions at speeds much beyond 6000 RPM. Thus, we were unable to verify that the engine could produce 43 HP at 6800 RPM, as predicted by AAI. During PLV advances the engine would overspeed after leveling off at 6000 RPM, although in some instances the engine would overspeed during PLV advances from idle without leveling off at 6000 RPM. The overspeed problem occurred due to a combination of unpredictable engine speed control and insufficient waterbrake response time. We increased the slew rate on the waterbrake inlet valve to help control the experienced rapid engine accelerations but this did not enable the waterbrake to properly control the engine accelerations. The waterbrake would have controlled the engine if the engine response to PLV advances was linear or predictable. The solution to the overspeed problem lies in a precisely calibrated, well tuned fuel injection control map. A well tuned fuel injection control map would allow smooth engine accelerations and decelerations throughout the full PLV range. This would allow us to operate the engine at the maximum RPM and determine the maximum power output.

Similar engine control problems precluded the completion of the engine calibration test. In this case, the problem involved the inability to set the engine at the required speed increments. Again, a well tuned fuel injection control map would allow precise control of engine speed and allow for the completion of the calibration test in a timely manner.

4.2.1.2 TURBOCHARGER MATCHING

In order to define a fuel injector control map, turbocharger performance must be considered. To accomplish a smooth engine acceleration, the fuel injector control must modulate the injector flow in a manner to provide a proper fuel and air mixture throughout the acceleration. In order to accurately do this, the air pressure and temperature (density) and flow rate entering the engine from the turbocharger must be known throughout the entire operating range. It is quite likely that the unpredictable response of the engine to PLV transients was related to the chosen turbocharger performance. A rich F/A mixture would reduce exhaust gas temperature and potentially cause a lag in generating boost pressure and thus a lag in RPM increase.

4.2.1.3 TURBOCHARGER DURABILITY

Two turbochargers (same model) were used during this test. At the conclusion of the test, both turbochargers had damaged or broken inlet guide vanes. From our investigation, we concluded that the turbochargers had been damaged by foreign object damage (FOD) as a result of the broken glow plug tips described below in section 4.2.1.4.

4.2.1.4 GLOW PLUG DURABILITY

The glow plug was powered by a DC power source and increased in temperature output as the voltage level was increased. Normally, the voltage level was set to approximately 12 VDC to start the engine, although on several occasions a higher voltage was required to get the engine started. The glow plug remained powered the entire time the engine was running.

During the test, glow plug tips broke off three times while the engine was running and caused damage to the rotor apex seals. In each case the engine trochoid housing was not severely scored as the broken glow plug tips exited the combustion chamber through the exhaust port before significant damage could occur. In another case, a failed glow plug tip actually caused a corner of the engine rotor to break off. A glow plug tip broke off a fourth time but remained in the prechamber, which prevented damage to the apex seals. We found that the glow plug tips were breaking while the engine was at high power and determined that the breakage was due to extremely high combustion temperatures which occur at these power conditions. We tested two different brands of glow plugs for our application, Beck/Arnley Y901R and Bosch (P/N 0250201021). Both brands of glow plugs failed during testing.

4.2.1.5 ROTOR SIDE SEALS

AAI inadvertently assembled engine S/N 0101-7 with an incorrectly sized rotor. The rotor width was too narrow which caused the gap between the end plate and the rotor to be beyond the operational specification. AAI reported a gap of 0.020 inches versus a maximum allowable gap of 0.013 inches. The excessive gap allowed combustion gas to travel beneath the side seals leaving carbon deposits which eventually caused the seals to stick.

4.2.1.6 FUEL DELIVERY SYSTEM

Fuel pressure fluctuations at the exit of the high pressure fuel pump made the engine difficult to start and caused the engine to stall frequently. AAI increased the displacement of the high pressure fuel pump from 400 cc per revolution to 500 cc per revolution to provide steady pressure. The problem was difficult to troubleshoot because the pump produced full pressure while it was dead-headed.

Fuel pressure fluctuations also occurred as a result of problems with the injectors and the solenoid valves. A failed spring in a main injector caused pressure fluctuations, and a complete loss of fuel pressure resulted when a solenoid valve failed.

4.2.2 DGII

4.2.2.1 LUBRICATION SYSTEM

As testing continued, an oil leak coming from the engine shaft around the location of the bearing/seal area (PTO side) grew to the point of requiring repair. DGII personnel replaced the bearing and seal. During the initial start after repair we noticed a small oil leak coming from inside the PTO shaft from the oil plug. DGII installed a new oil plug. During the next test period, the engine exhibited an engine oil pressure of 50 psig, a decrease of 20 psig from the normal 70 psig. We discussed the pressure decrease with the DGII representative who stated that testing could continue as long as the oil pressure remained above 40 psig. The pressure did remain above 40 psig for the rest of the test.

4.2.2.2 PTO SHAFT KEY

At the time the engine oil bearing and seal described above were replaced, the engine flywheel was reinstalled onto the engine PTO shaft. Our facility flywheel was reconnected to the engine flywheel and universal driveshaft connecting the engine to the waterbrake. During initial start attempts the facility and engine flywheels spun off of the engine shaft and impinged on the protective cover (scattershield) that surrounded the universal driveshaft. Upon inspection we noticed that the PTO shaft key had sheared off. DGII installed a new shaft key and we modified our flywheel to lock directly onto the engine shaft, thereby eliminating the possibility of any axial movement.

4.2.2.3 LOW SPEED OPERABILITY

Low speed operation was limited to 20 ft-lbs and 4500 RPM while operating under automatic propeller load dynamometer control and 6.5 ft-lbs and 4000 RPM under speed governing dynamometer control. Engine stability increased with higher speeds and loads. The engine was not delivered with any recommended turbocharger control schedule and the wastegate remained closed during all engine operation. We investigated the possibility of excess engine intake air at idle as causing the low load stability problems. The stoichiometric air to fuel ratio was approximately 15:1 and at the higher loads the DGII engine ran stably with an air to fuel ratio in the range of 22:1 through 25:1. As the load decreased, the air to fuel ratio increased due to the closed turbocharger wastegate. As load decreased into the range of 20 to 24 ft-lbs under automatic propeller load control (6 to 10 ft-lbs under speed governing control), the engine became unstable. This was due to the high air to fuel ratio (33:1 up to 35:1) at this point, as the mixture at this condition was too lean to promote proper combustion. As a result, the engine would exhibit large changes in power output which would cause the engine to stall. In an effort to dismiss the dynamometer control response settings as the cause of the stability problems, we fine tuned the dynamometer controls to provide more accurate control. This had no effect as torque continued to vary +/- 2.5 ft-lb of setting and engine speed fluctuated +/- 200 RPM while operating in automatic propeller control mode. We concluded that the engine was not exhibiting proper combustion characteristics at the low end and therefore could not maintain a stable power output. Another possibility was a problem with operation of the fuel delivery system at low speed (below 4000 RPM). We decided to discontinue investigation below the point of instability.

4.2.2.4 TURBOCHARGER COOLING JACKET

The turbocharger turbine inlet cooling jacket developed an internal leak during the final portion of the 15K ft engine calibrations. We shut off the cooling water supply, ignition, and fuel supply and cranked the engine for a number of drying cycles. We drained the oil and replaced it with new oil. We then started the engine and continued with the altitude calibration at power settings not requiring turbine inlet cooling.

4.2.2.5 ROTOR

On 14 October 1992, after accumulating 33.4 hours of operation, the engine stalled while we were attempting to determine the low end operating point of the engine on the 70 kt propeller load curve. During further starting attempts, our instrumentation showed no signs of engine shaft rotation. A teardown inspection and analysis were conducted to investigate the cause of the engine failure. This teardown inspection is included as Appendix H. A crack in the rotor, which originated on the journal bearing seat, was examined. The crack did not appear to be due to fatigue as it had the microscopic appearance of a tensile overload failure with the initiation point being a very thin wall between the journal bearing seat and a balancing hole. The likely sequence of events points toward an improperly placed rotor balance hole, the wall of which cracked and allowed the journal bearing to "walk" out. Eventually the bearing moved out far enough so that the stresses grew on the portion of the bearing which still remained in contact with the bearing seat. This situation continued until the stress reached a critical level and the bearing could no longer support the load, causing the engine to seize.

4.2.3 SwRI

4.2.3.1 FUEL INJECTOR LINES

During testing on 28 September 1992 (9.5 engine hrs) a high pressure fuel injection line sheared at the injector. This was due to the excessive vibration the injection lines encountered because the fuel system was hard mounted to the engine without any vibration isolators. The injection line was replaced without modification and no other injector line anomalies occurred during the test.

4.2.3.2 FUEL PUMP RACK CONTROL

During testing on 24 September 1992 (9.3 engine hrs) the fuel pump rack control rod on the fuel injection pump broke at its thinnest point and required welding to repair. This was a thin rod not designed to operate in such a high vibration environment. Once repaired, it did not fail again.

4.2.3.3 570 cc EXHAUST PIPE

During testing with the 570 cc exhaust pipe, excess fuel collected in the expansion chamber (caused by incorrect timing of the reverse pressure wave produced by the tuned pipe) and ignited inside the pipe. This clearly indicates the 570 cc pipe was not the optimum pipe for this engine.

4.2.3.4 TAPERED PTO OUTPUT SHAFT

The 10:1 tapered output shaft coupling used on the engine slipped during testing. This caused all engine timing parameters to be in error although they appeared correct on our control room instrumentation. As a result, the engine became very difficult to start and when it did start, made no appreciable power. Once the problem was discovered and corrected, engine performance returned to what was previously demonstrated.

4.2.3.5 SPARK PLUG FOULING

Repeated fouling of spark plugs occurred during testing. The fouling occurred while the engine coolant temperature was increasing to its operational value. The majority of fouling can be attributed to the incorrect engine timing mentioned above, although some fouling did occur with the correct timing. It is important to note that once a plug had been fouled, it could not be reused, even after it had been cleaned. Reuse of such a plug resulted in immediate re-fouling. The reason for the initial fouling is most likely that the metering pump for the engine lubrication was wired open during all development. This was done to provide adequate lubrication to the engine as the effect of fuel washing and diluting the lubricating oil was not known. The extra oil introduced into the combustion chamber was likely responsible for the repeated spark plug fouling. This was especially true if the engine did not start quickly, as extended cranking allowed more unburned lubricating oil to accumulate in the combustion chambers.

4.2.3.6 CYLINDER HEAD THREADS

Due to repeated insertion and removal of the spark plugs during testing at both SwRI and NAVAIRWARCENACDIVTRN, the spark plug threads wore and had to be replaced with Heli-Coil brand thread inserts. The threads for the fuel injector hold down clamp bolts were also replaced with Heli-Coil inserts to prevent the bolts from being pulled from the head. Whenever the engine was shut down, removal of the spark plugs would result in removal of the Heli-Coil as well. This was due to the expansion ratio of the aluminum head being greater than that of the stainless steel Heli-Coil.

4.2.3.7 CANDY DRIVE DIFFERENTIAL FAILURE

A Candy Drive differential, used to alter fuel injection timing, failed during testing. The failed unit was replaced by a second unit and testing was continued. The drive was disassembled for inspection and it was determined that the central gear of the worm drive had cracked and lost contact with the top worm gear. The second unit did not fail at any time during testing. The Candy drive was used exclusively as a research tool during testing and will not be incorporated in a final version of the engine.

4.3 ACHIEVEMENT OF HFE PROGRAM GOALS

Please refer to Tables 8, 9, and 10 for assessment of HFE program goals.

4.3.1 AAI POTENTIAL ASSESSMENT RATIONALE

a. <u>50 HP Maximum Power</u> - The maximum demonstrated output power of 32.0 HP @ 5898 RPM was limited by the maximum RPM at which the engine could be operated, as discussed in sections 4.1.1.4 and 4.2.1.1 of this report. The calculated BMEP at this condition was 121.0 psia. Assuming that the engine control problem can be resolved, with a constant BMEP and 8000 RPM operation, the maximum expected horsepower is calculated to be 44.0 HP.

b. <u>0.5 BSFC</u> - The HFE program goal was met.

c. <u>50 lb Maximum Weight</u> - The demonstrated dry weight was 71.0 lbs. Reduction of engine weight can be obtained by modifying the engine design and the manufacturing process. A new casting for the engine has been manufactured which will yield a 14.0 lb weight reduction. Additional weight reduction can be obtained through individual component redesign and material changes. Therefore, the 50 lb weight goal may be obtainable.

d. <u>7500 ft Start</u> - The engine was successfully started at the correct inlet pressure to simulate 7500 ft altitude conditions, although, due to a facility problem, the inlet temperature (72°F) was higher than the 32°F required to simulate an altitude of 7500 ft. The lower temperature will have an adverse effect on starting, as a longer cranking time will be required to develop the required combustion chamber temperature for a successful start.

e. <u>0 to 15000 ft Altitude Operation</u> - The engine was run up to a simulated altitude of 7500 ft. Further altitude testing was not attempted as testing ended during the sea level portion of our test plan due to engine speed control problems. With the inlet boost pressure from the turbocharger, altitude operation to 15000 ft appears to be achievable.

f. <u>-25°F to 125°F Operation</u> - Once running, the engine should not have any difficulty operating at the temperature extremes. However, as with most engines, starting the engine at the cold extreme may be difficult.

g. <u>300 hr Durability</u> - Durability can only be assessed from actual test data and a durability test was not conducted.

h. <u>Multi-fuel Operation</u> - We did not test the engine with JP-8 or Diesel fuel as planned testing with JP-5 had not been completed. However, AAI has been running a smaller displacement air cooled engine on Diesel and Jet A fuels using the technology developed in this HFE program. Because of this, the engine should be able to operate on all three heavy fuels.

4.3.2 <u>DGII POTENTIAL ASSESSMENT RATIONALE</u>

a. <u>50 HP Maximum Power</u> - The HFE program goal was met.

b. 0.5 BSFC - Further development work in the area of combustion chamber and fuel system optimization should prove beneficial in reducing BSFC to our desired goal.

c. 50 lb Maximum Weight - Removal of the integral starter motor and associated gearing, combined with new light weight castings which eliminate excess material, can potentially reduce the 102.0 lbs engine weight by 22 lbs.

d. 7500 ft Start - The HFE program goal was met.

e. 0 to 15000 ft Altitude Operation - The HFE program goal was met.

f. -25°F to 125°F Operation - Once running, the engine should not have any difficulty operating at the temperature extremes. However, as with most engines, starting the engine at the cold extreme may be difficult.

g. 300 hr Durability - Durability can only be assessed from actual test data and a durability test was not conducted.

h. Multi-fuel Operation - Due to the unexpected engine failure, we could not proceed beyond the engine calibration portion of our test. Although the engine was not operated at NAVAIRWARCENACDIVTRN on JP-8 or Diesel fuels, confidence of multi-fuel operation is high due to prior contractor development testing on Diesel fuel and the similarities in chemical composition that exist between JP-5 and JP-8 fuels.

4.3.3 SwRI POTENTIAL ASSESSMENT RATIONALE

a. 50 HP Maximum Power - Currently producing 35.3 HP @ 5000 RPM with an improper exhaust system and non-optimal port timing, the per cylinder BMEP is 168.4 psig. Assuming this BMEP can be held constant, extrapolating to 6000 RPM results in 42.0 HP. Simulated turbocharger testing done at SwRI produced 41 HP @ 5000 RPM with 5.0 psig of boost pressure. This corresponds to a BMEP of 195.6 psig per cylinder. Extrapolating this to 6000 RPM indicates 49.2 HP is available. Increasing boost levels above 5.0 psig results in a linear horsepower increase until the durability of the engine becomes the limiting factor. SwRI also demonstrated a BMEP of 243.3 psig (51.0 HP @ 5000 RPM) while running the engine on gasoline. Therefore, our analysis indicates that the 50 hp HFE goal is attainable.

b. 0.5 BSFC - Increasing fuel injection pressure from 2800 psig to 10000-15000 psig should provide better atomization and improved operability with approximately a 25% improvement in BSFC over the entire engine speed range. By incorporating the correct exhaust system and engine port timing, the HFE BSFC goal is obtainable.

c. 50 lb Maximum Weight - Although the engine weight of 50 lbs meets our HFE goal, the incorporation of lightweight fuel injection system components (injectors, lines, couplings, and fuel injection pump) could further reduce engine weight by approximately 5.0 lbs.

d. 7500 ft Start - Although not attempted during testing, the reduced intake charge density should not introduce any starting problems at this altitude.

f. 0 to 15000 ft Altitude Operation - No altitude testing was attempted. There is no reason to believe the engine would not operate in the desired altitude range for this program, although the power output would decrease in direct proportion to the change in inlet air density (the propeller load also lapses with altitude).

e. -25°F to 125°F Operation - Operation at -25°F would require fuel system heaters to prevent the heavy fuels from waxing and the engine may require extended cranking time to heat the combustion chamber properly for fuel atomization. Because the engine uses low friction roller bearings and has few moving parts, if the fuel temperature is maintained above the cloud point of the fuel, the engine should start anywhere in this temperature range.

f. 300 hr Durability - Durability can only be assessed from actual test data and a durability test was not conducted.

g. Multi-fuel Operation - SwRI performed all testing on JP-8. SwRI attempted to use diesel fuel with unsatisfactory results due to the lack of injection pressure to properly atomize the fuel. Incorporating a very high pressure injection system would enable the engine to run on all three heavy fuels, but additional development is required to determine if performance or operability would suffer significantly due to differences in fuel composition.

5.0 CONCLUSIONS

a. The technologies developed and demonstrated in the HFE program indicate that the UAV operational requirement for the elimination of gasoline can feasibly be met with heavy fuel engine propulsion systems.

b. The technologies demonstrated appropriately relate to air vehicle applications with weights of nominally 500 lbs or more.

6.0 RECOMMENDATIONS

a. Implement HFE technology to enhance commonality and eliminate the use of gasoline in DoD UAV systems.

b. Pursue heavy fuel engine technology transition and maturation efforts via an Engineering and Manufacturing Development Program (EMDP) to enhance air vehicle/engine integrability aspects.

LIST OF SYMBOLS AND ACRONYMS

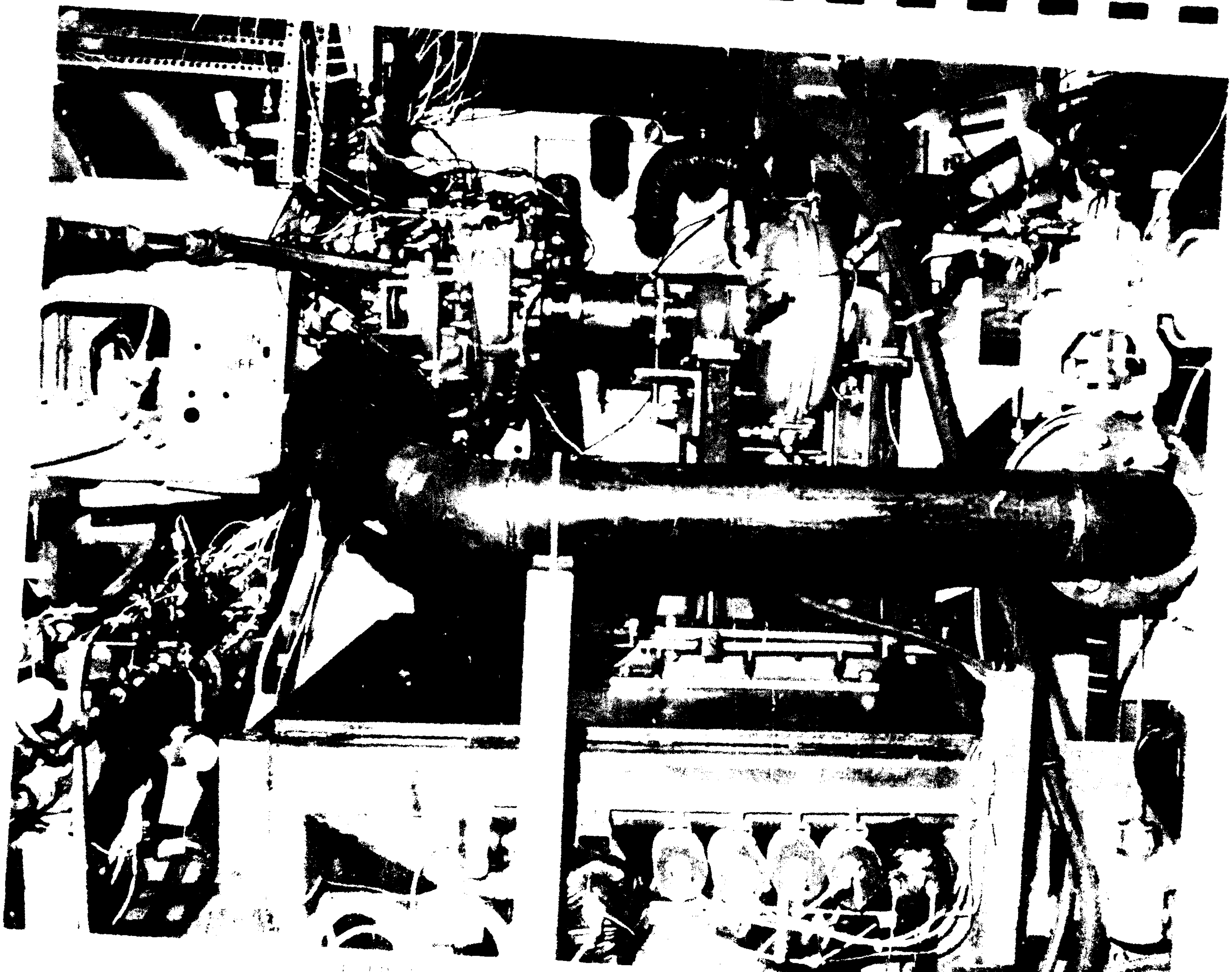
Symbol	Nomenclature	Units
AAI	AAI Corporation	-
Accel.	Acceleration	
BMEP	Brake Mean Effective Pressure	lb/in^2
BSFC	Brake Specific Fuel Consumption	lb/hp-hr
cc	Cubic Centimeter	-
CCW	Counter-clock Wise	-
cu. in.	Cubic Inches	in^3
Decel.	Deceleration	-
DGII	Defense Group Industries, Inc	-
°C	Degree Centigrade	°C
°F	Degrees Fahrenheit	°F
DoD	Department of Defense	-
ECU	Electronic Control Unit	-
EPROM	Erasable Programmable Read-only Memory	-
HFE	Heavy Fuel Engine	-
HP	Horsepower	hp
HPENGR	Engine Horsepower, Referred	HP REF
hr	Hour	hr
HSV	High Speed Solenoid Valve	-
in.	inches	-
InHgA	Inches of Mercury, Absolute	-
InHgD	Inches of Mercury, Differential	-
kg	Kilogram	kg
kt	Knot	naut. mile/hr
lb	Pounds	lb
m	Meter	m
MAP	Engine Manifold Pressure	lb/in^2
mm	Millimeters	-
MTBF	Mean Time Between Failure	-
NENG	Engine Speed	RPM
PBOSTA	Engine Inlet Boost Pressure	IN HG
PEINL	Engine Turbocharger Inlet Pressure	IN HG
PEINLA	Average Engine Inlet Pressure	IN HG
PEINDS	Desired Engine Inlet Pressure	IN HG
PLA	Power Lever Angle	%
PLV	Power Lever Voltage	Volts
POIL	Engine Oil Pressure	lb/in^2
PSIA	Pounds Per Square Inch Absolute	lb/in^2
PSI	Pounds Per Square Inch	-
PSIG	Pounds Per Square Inch Gauge	lb/in^2
PTO	Power-Takeoff	-
RPM	Revolutions Per Minute	rpm
rev.	Revolution	-
SEC	Seconds	-

LIST OF SYMBOLS AND ACRONYMS, CONT'D

Symbol	Nomenclature	Units
S/N	Serial Number	-
SFC	Specific Fuel Consumption	
TBOOST	Engine Air Inlet Temperature	°F
SwRI	Southwest Research Institute	-
TDC	Top Dead Center	-
TEINL	Engine Inlet Air Temperature	°F
THEAD	Engine Cylinder Head Temperature	°F
TORQDS	Torque Desired (setpoint)	Ft-Lb
TORQUE	Engine Torque	Ft-Lb
TURINL	Turbocharger Inlet (Eng Exh) Temperature	°F
TUROUT	Turbocharger Exhaust Temperature	°F
UAV	Unmanned Aerial Vehicle	-
VDC	Volts, Direct Current	volts
vs.	Versus	-
WBIV	Water Brake Inlet Valve Position	%
WOT	Wide Open Throttle	-

REFERENCES

1. UAV/JP TASK NO. PEO(CU)-UD3-2A24-009-00000, NAPC WUA No. 517



... Corporation Heavy Fuel ... Test Cell 6...

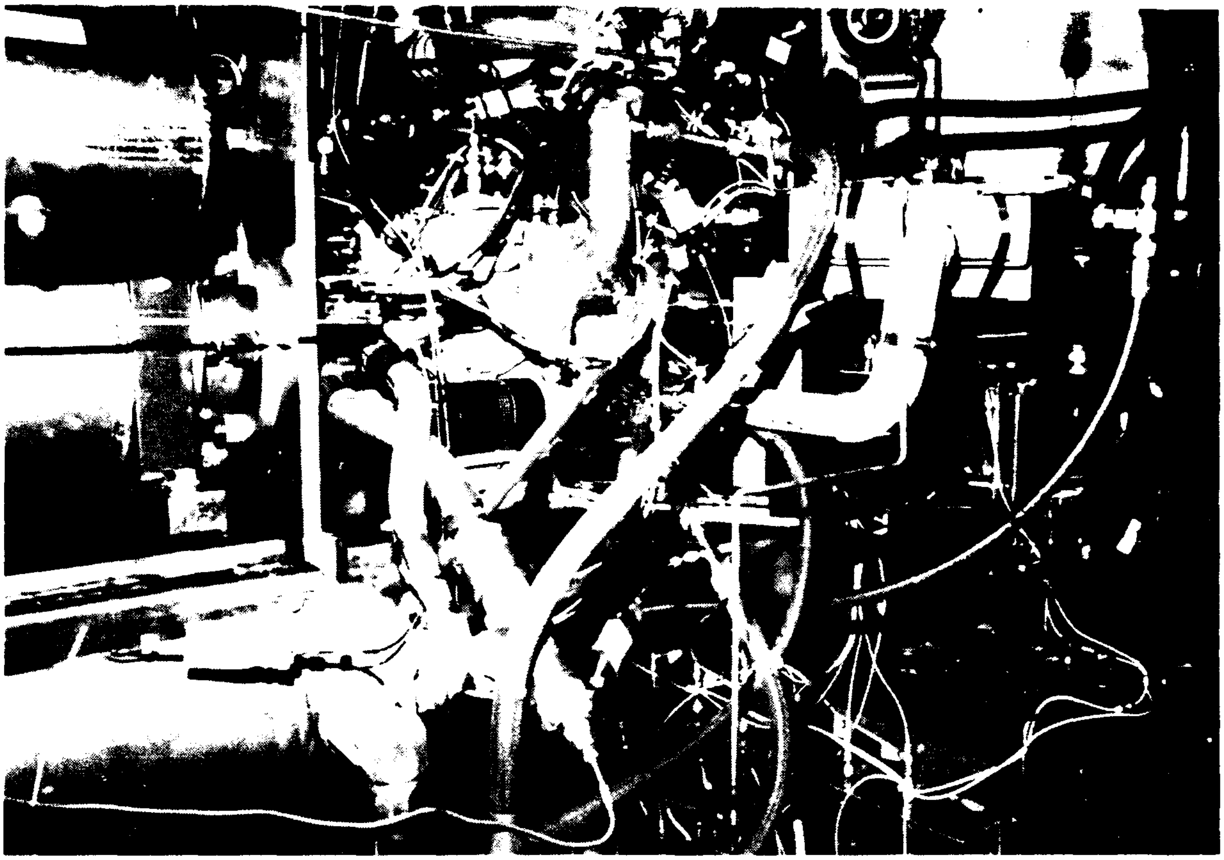


FIGURE 2a. Defense Group Industries Inc Heavy Fuel Engine Installed in Test Cell 6W

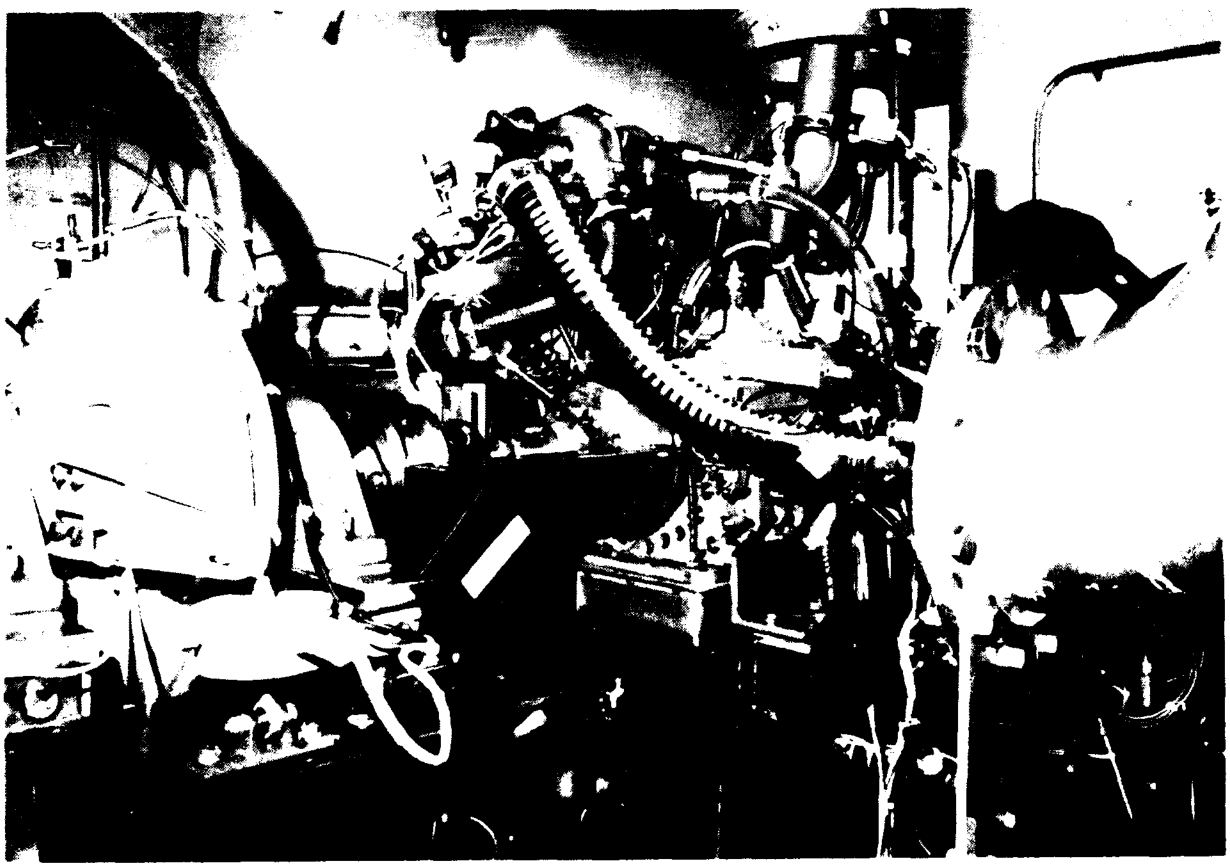


FIGURE 2b. Defense Group Industries In[illegible] Heavy Fuel [illegible]

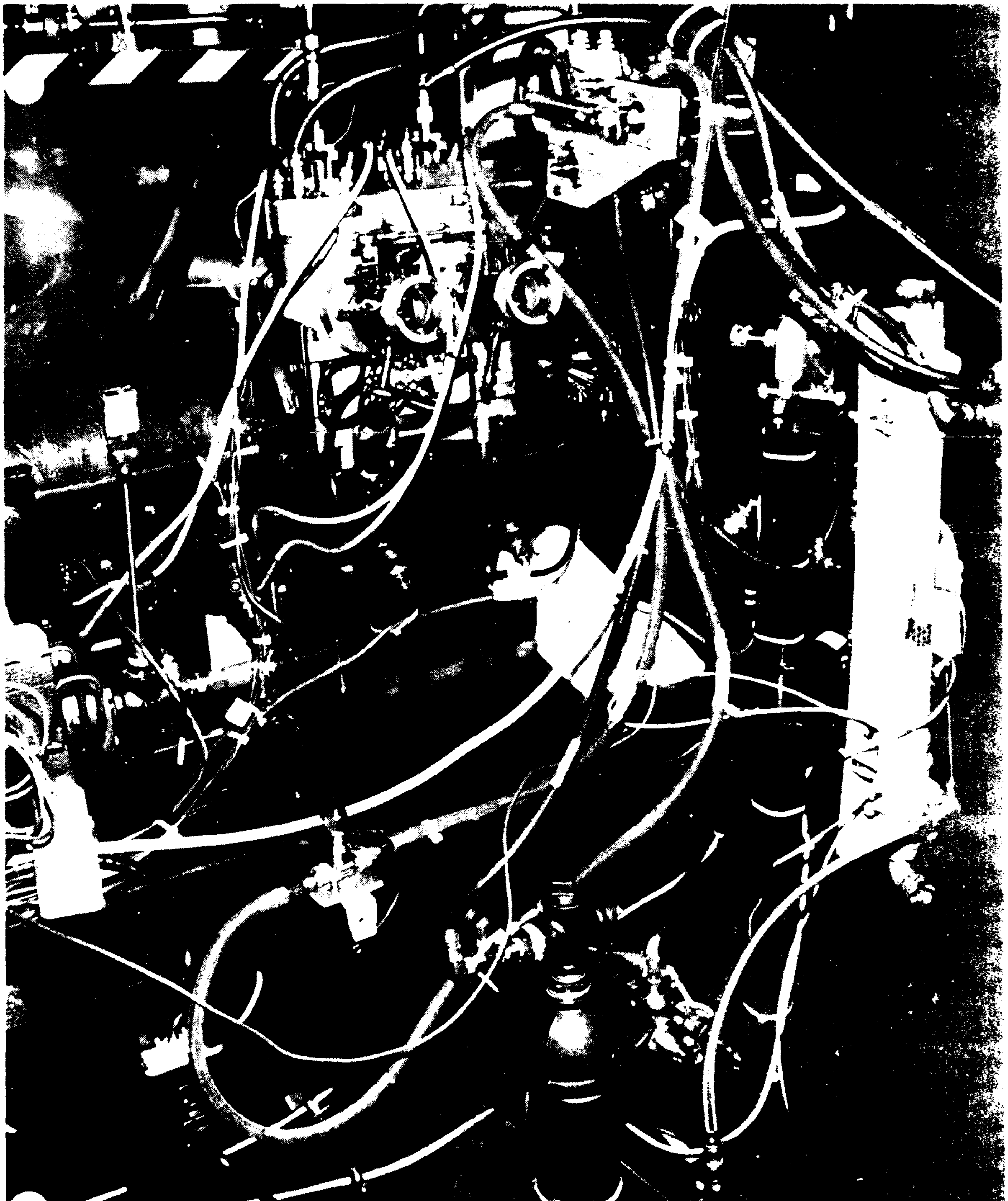
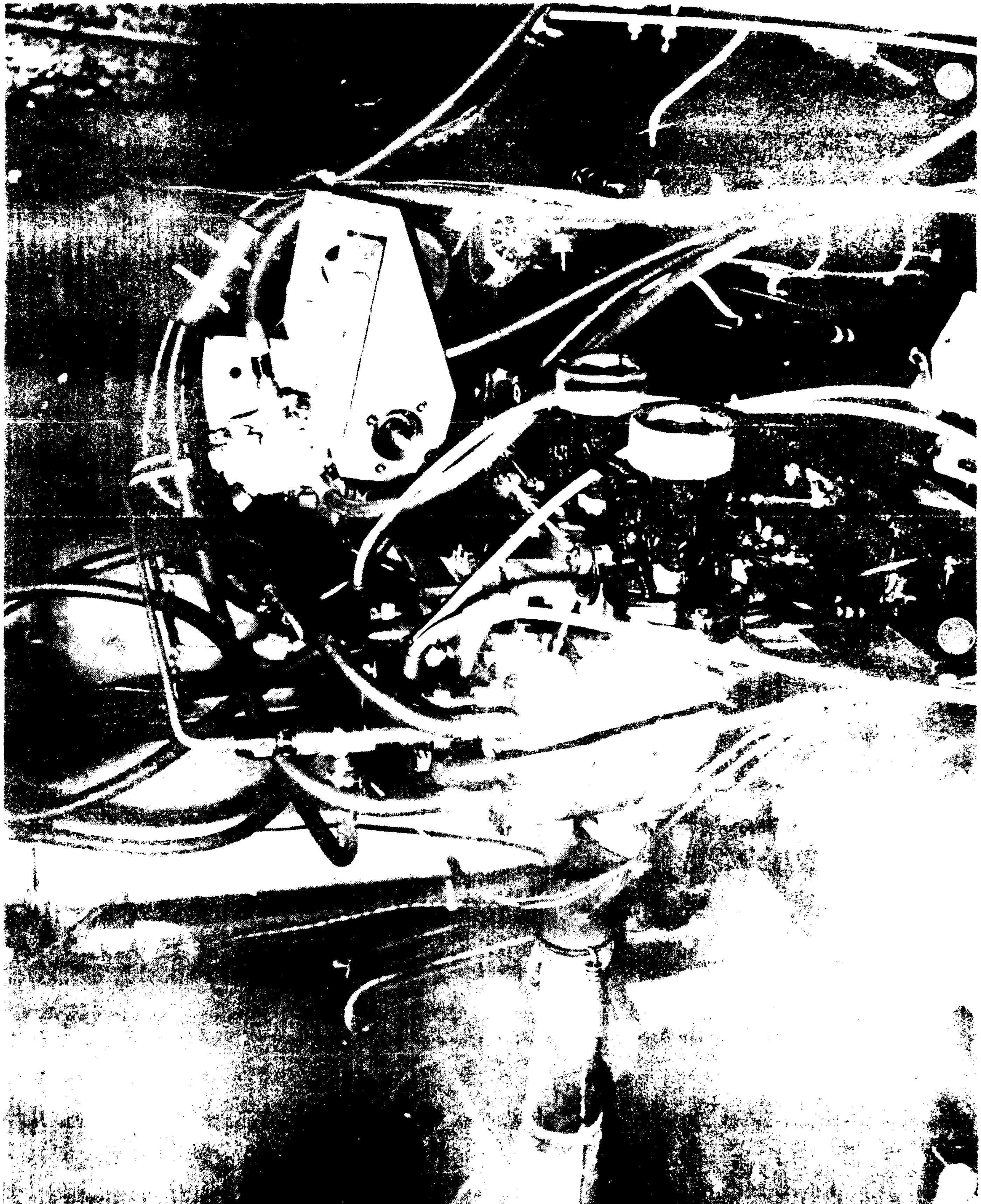


FIGURE 2. Southwest Research Institute [illegible]
[illegible]



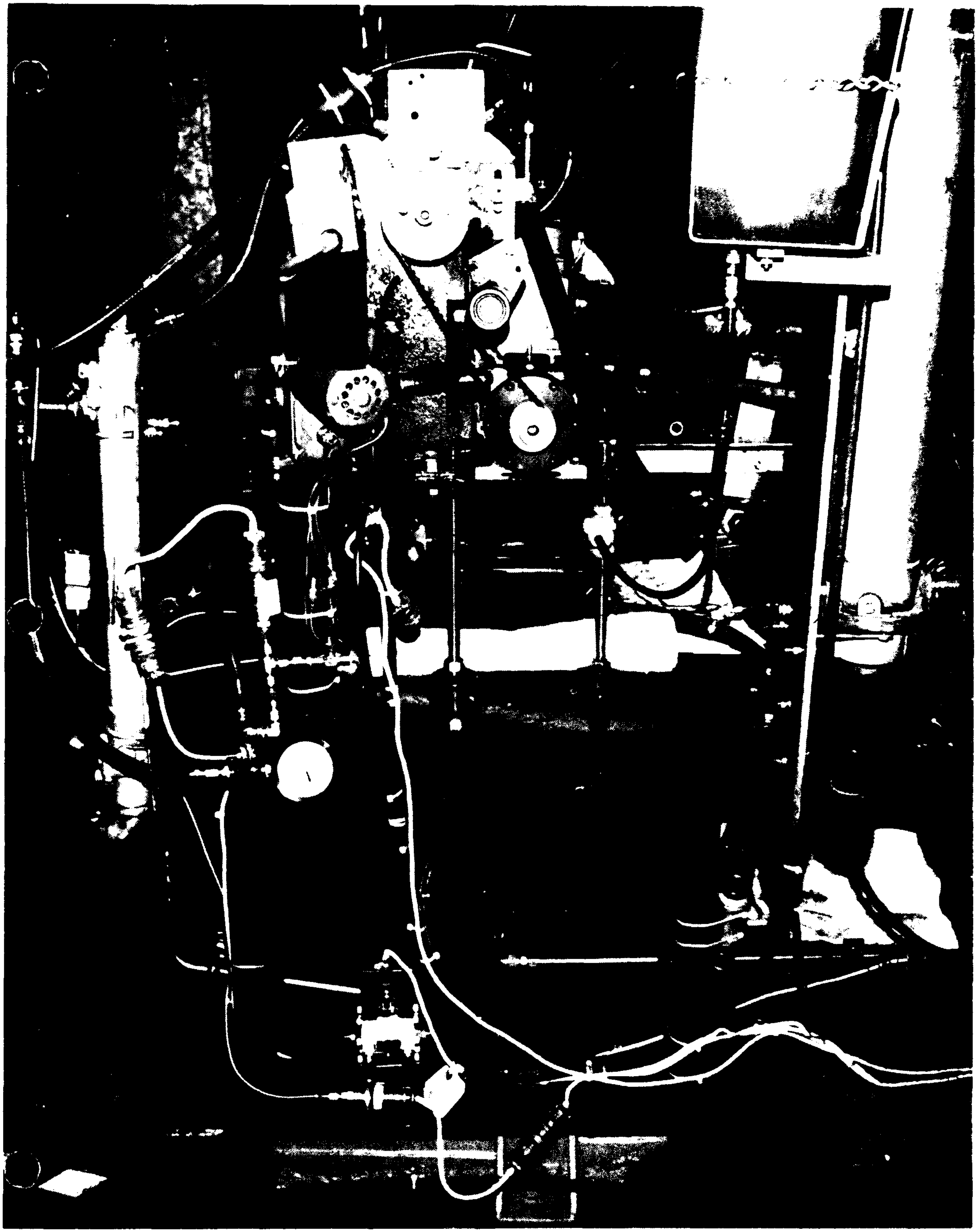


FIGURE 6. Rear View of SwRI Engine Showing Candy Differential and Electric Servomotor

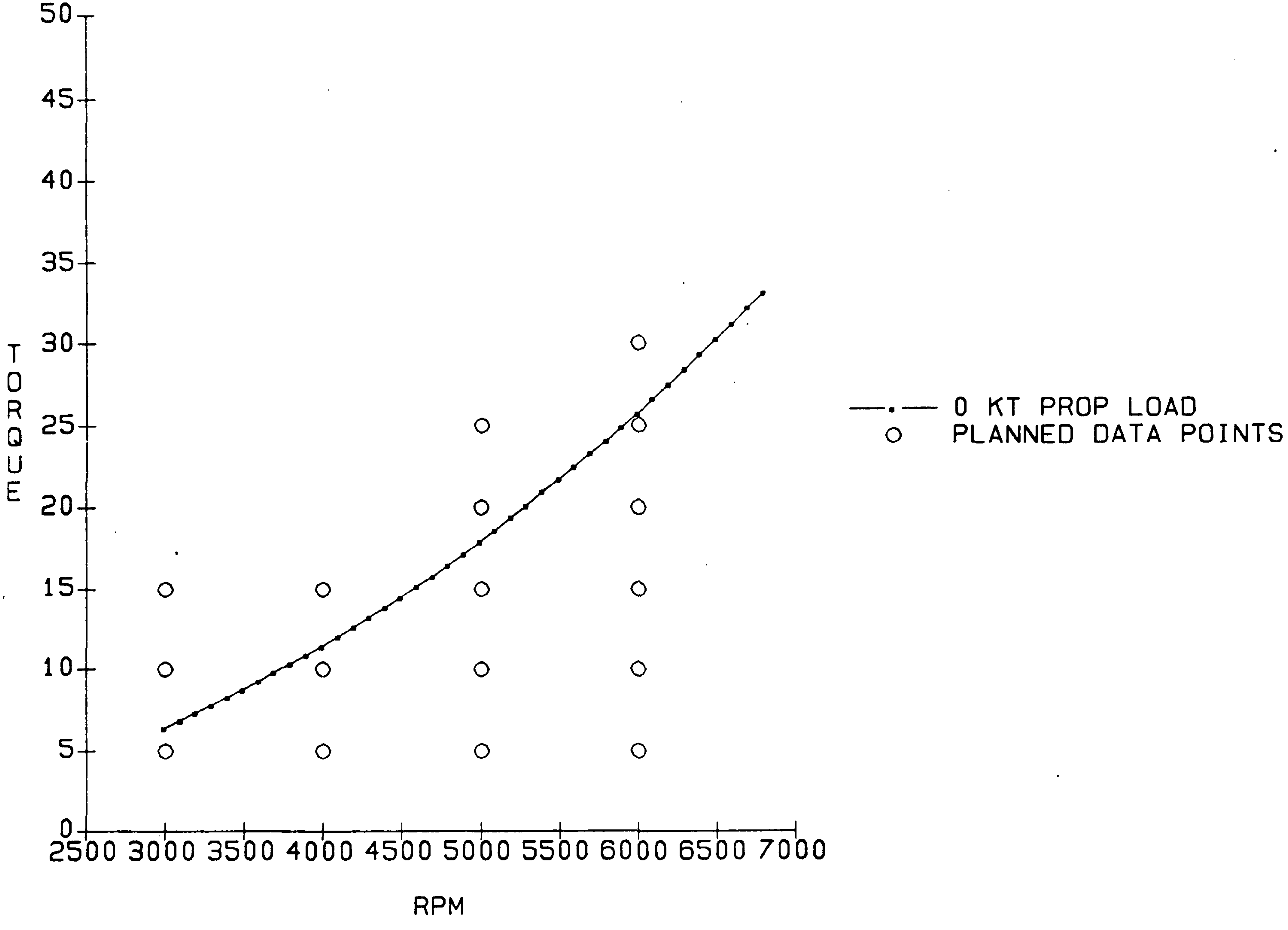


FIGURE 7. AAI HFE; Planned Calibration Test Points

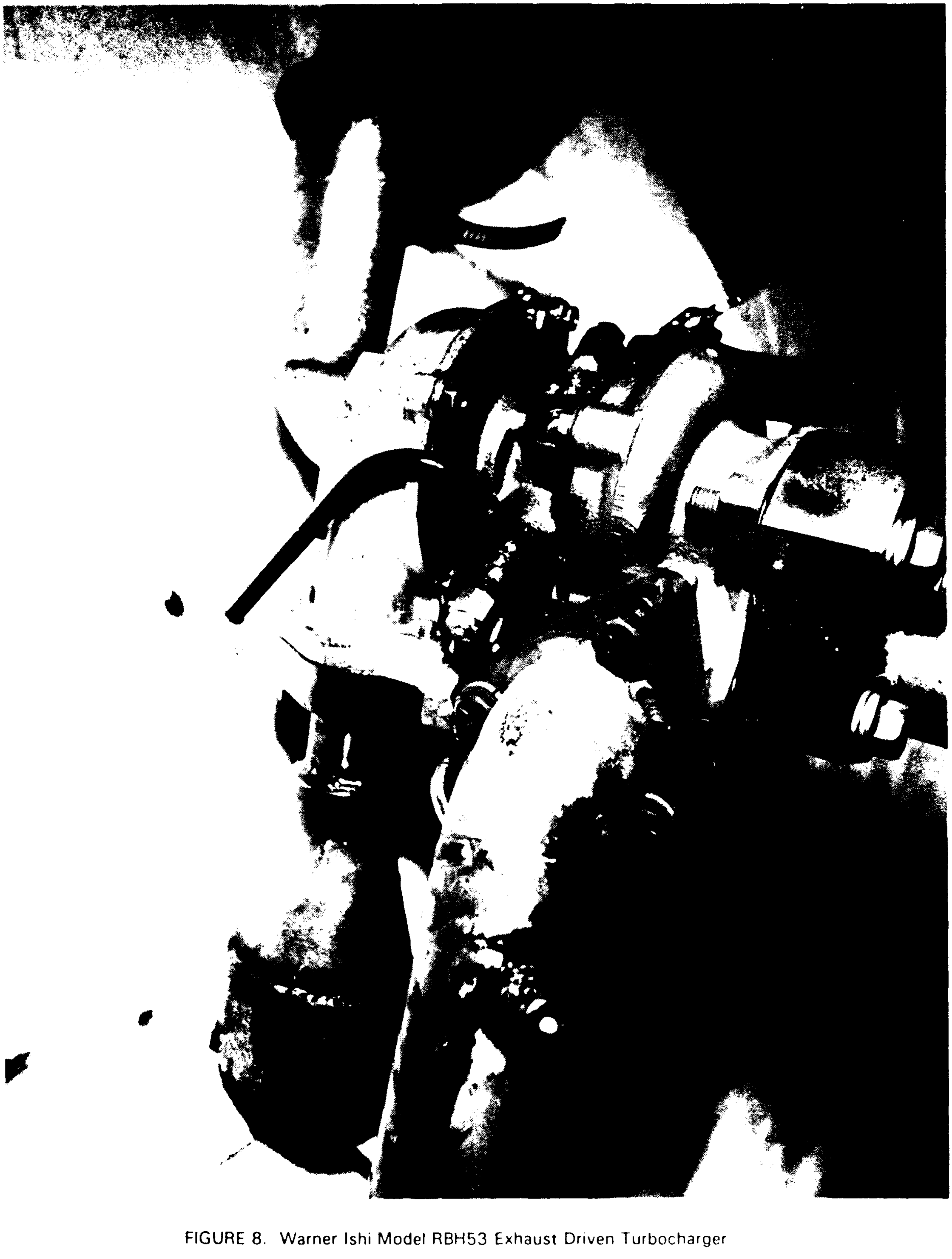


FIGURE 8. Warner Ishi Model RBH53 Exhaust Driven Turbocharger

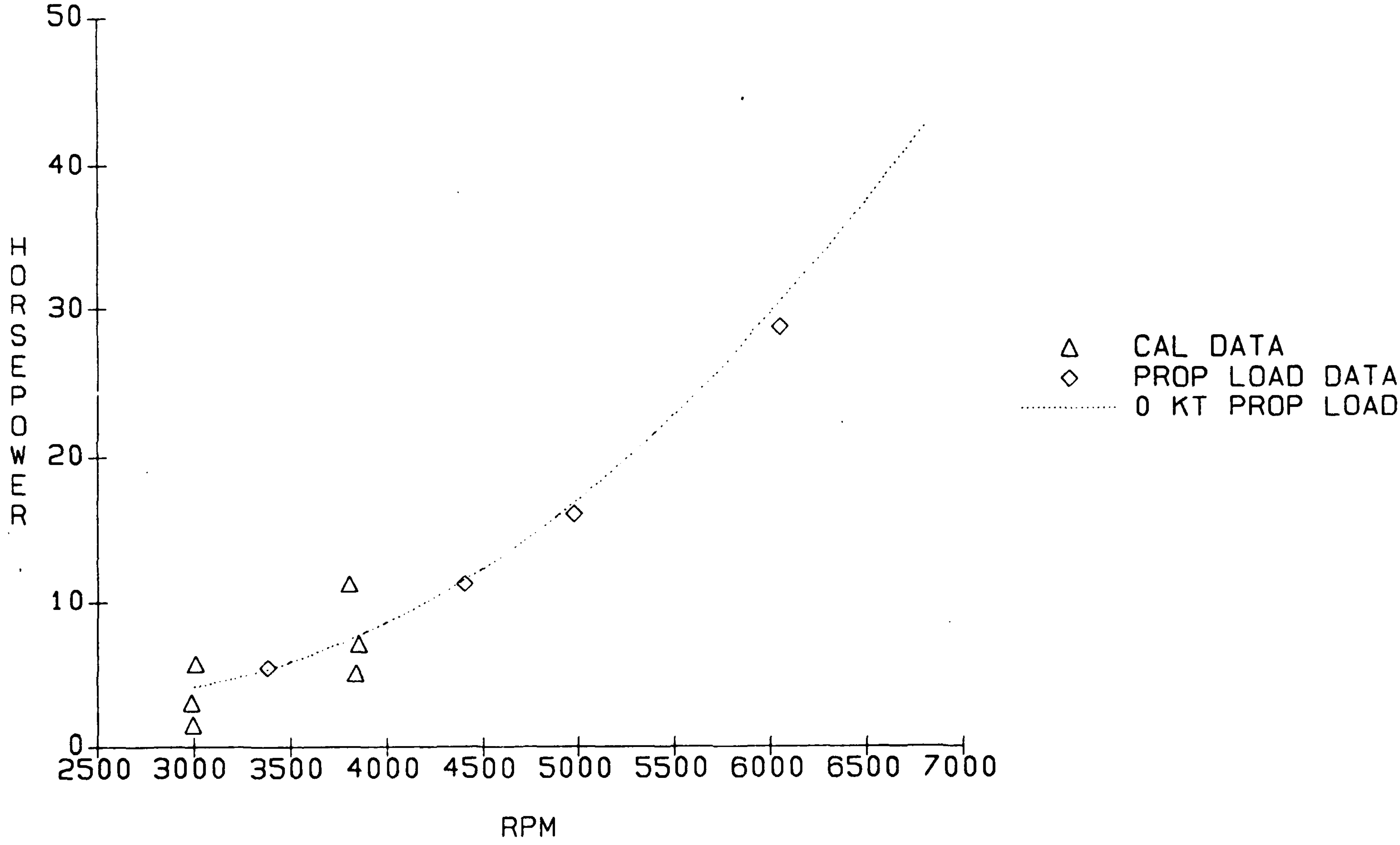


FIGURE 9. AAI HFE S/N 0101-2; 8:1 Compression Ratio Rotor, Sea Level, Horsepower vs Engine Speed

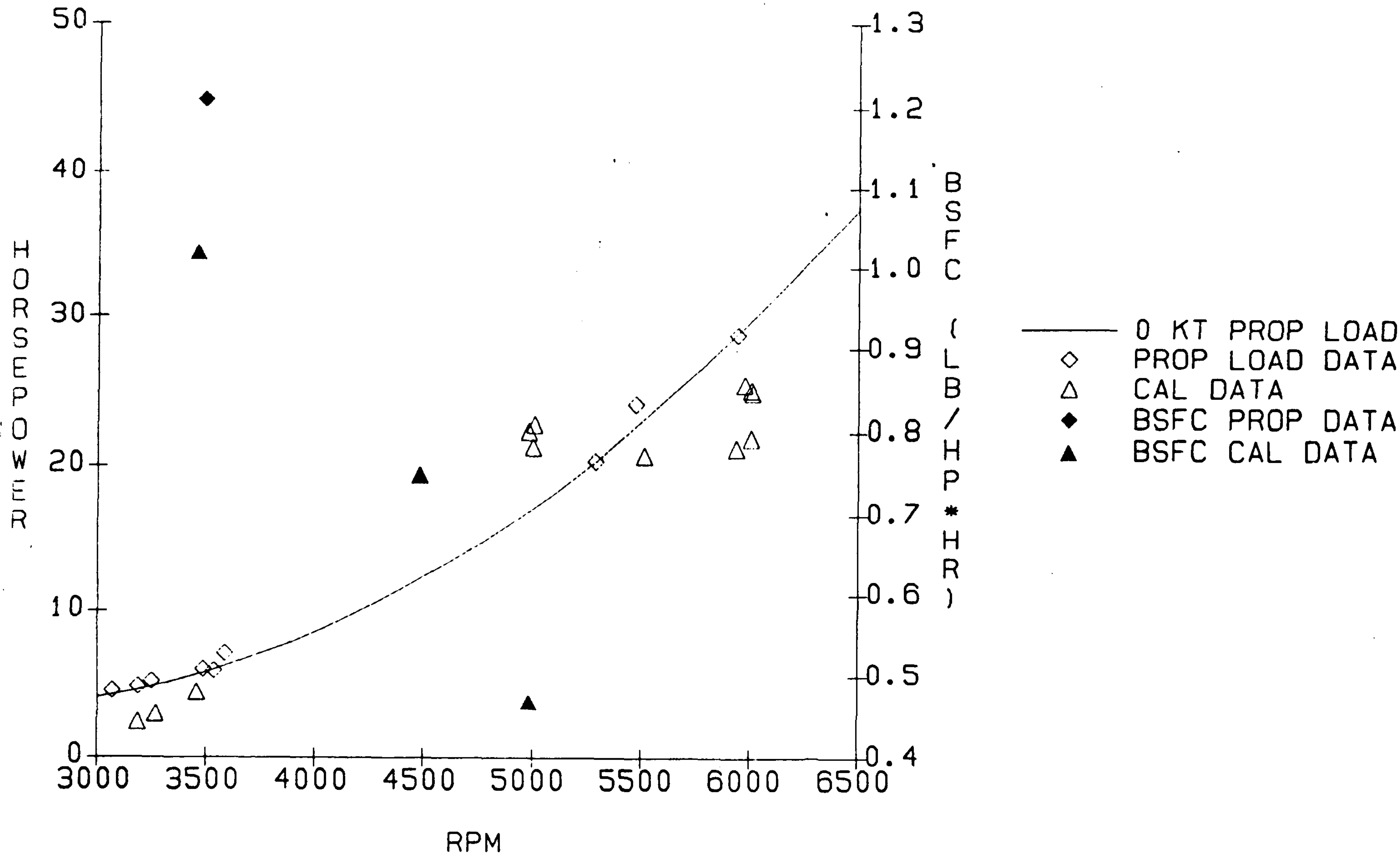


FIGURE 10. AAI HFE S/N 0101-4; 8:1 Compression Ratio Rotor, Sea Level, Horsepower vs Engine Speed

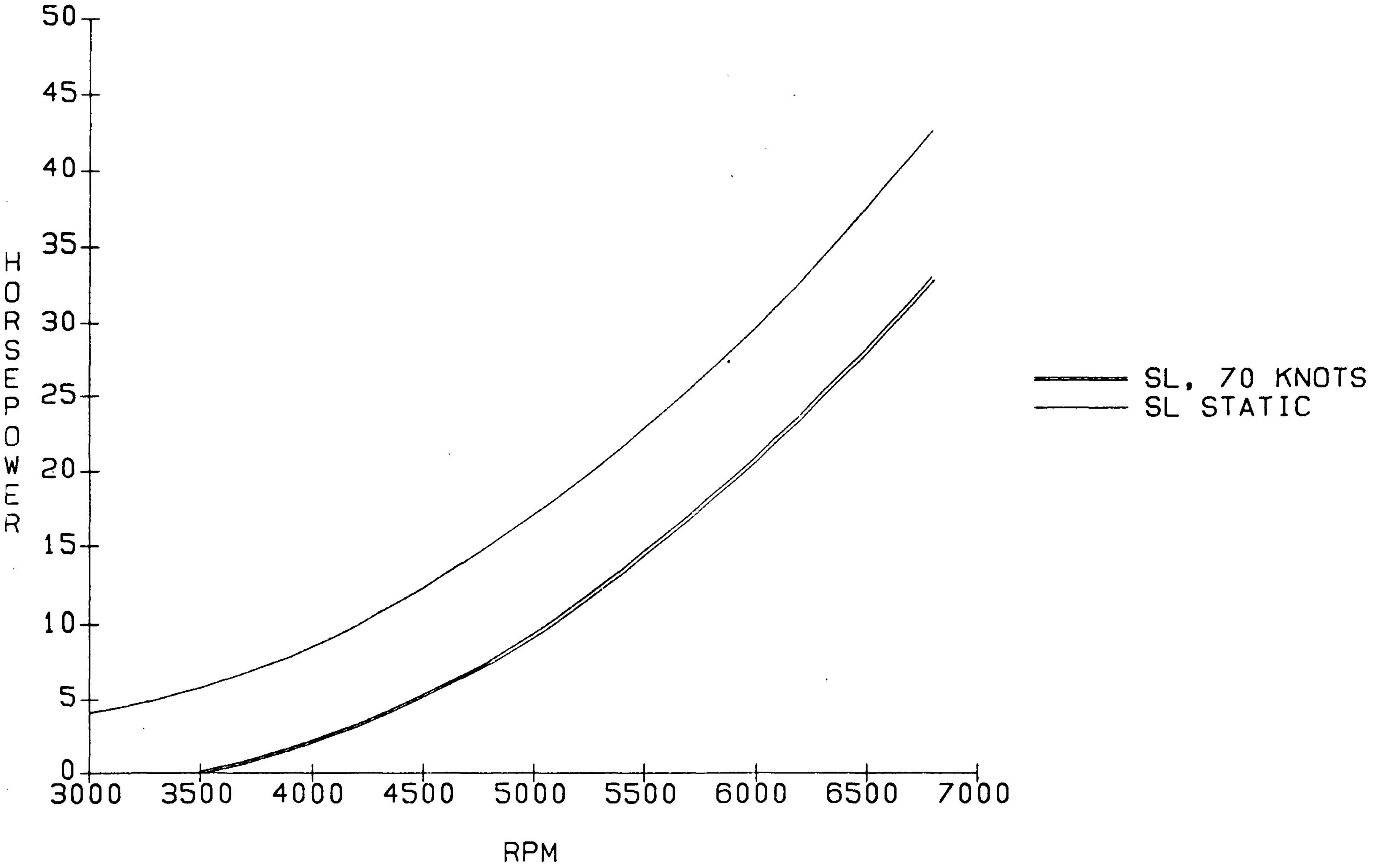


FIGURE 11. AAI HFE; Test Propeller Load Curves

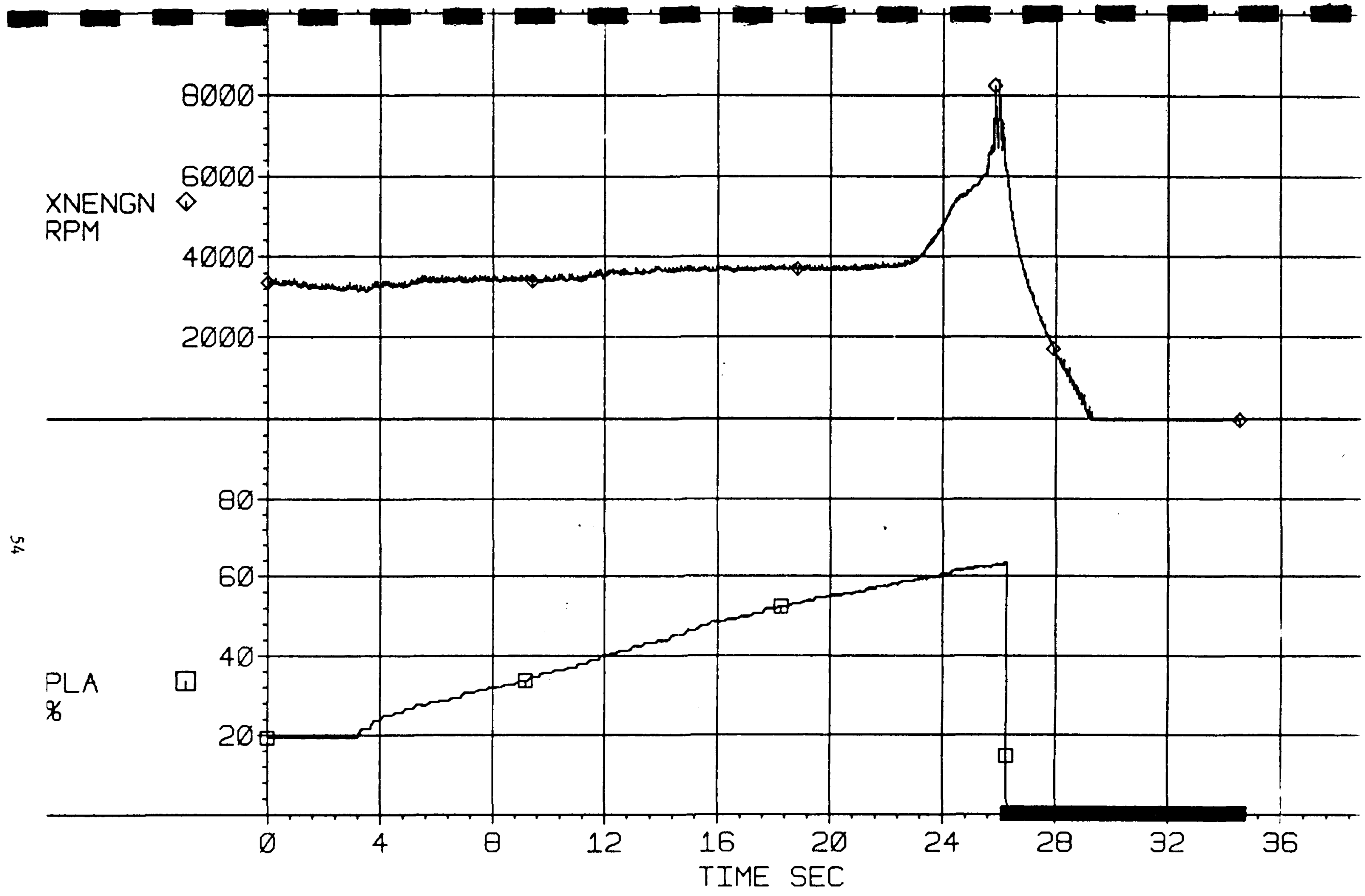


FIGURE 12. AAI HFE; Transient Response to PLV Advance and Engine Over-Speed Shutdown

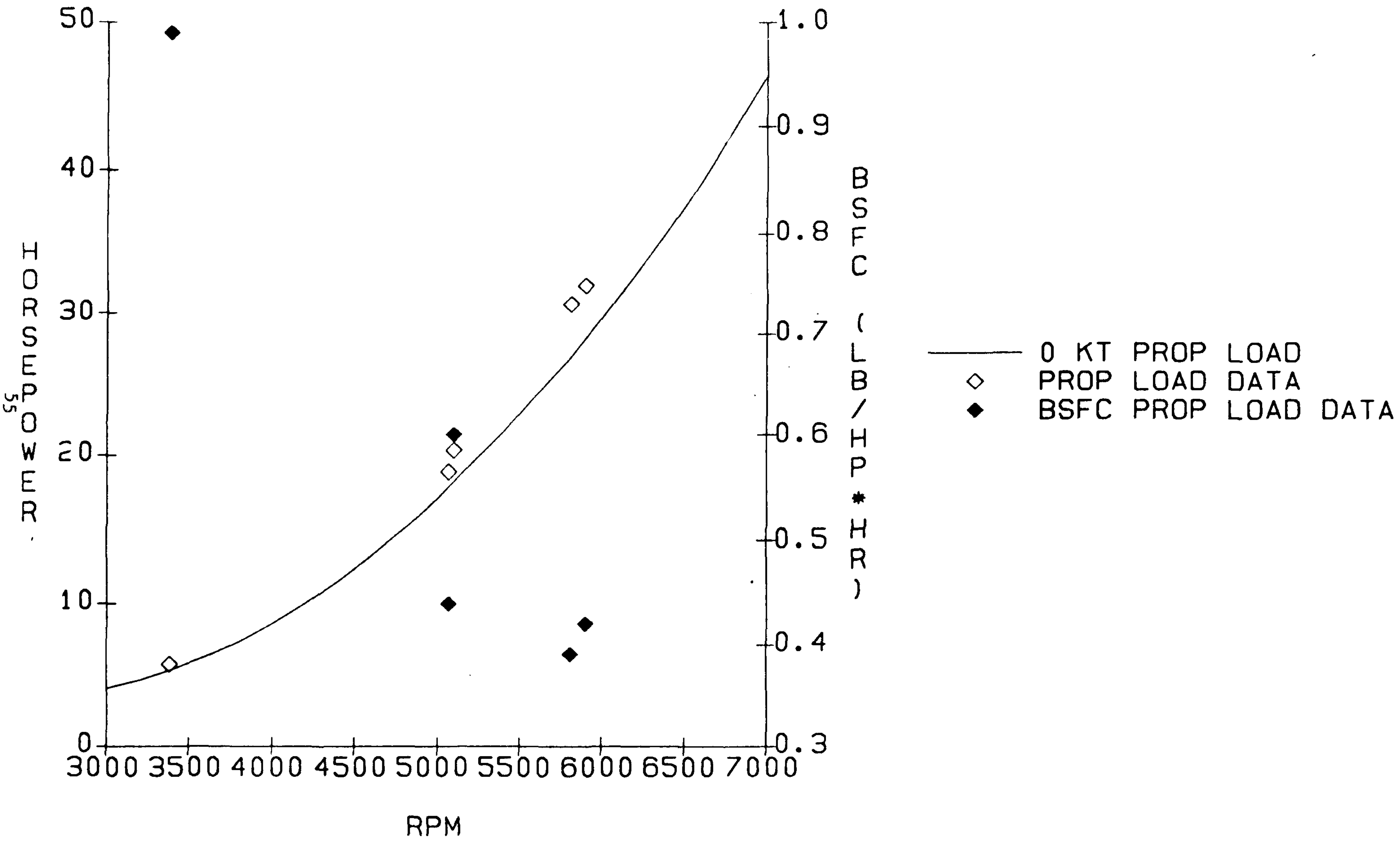


FIGURE 13. AAI HFE S/N 0101-7; 8:1 Compression Ratio Rotor, Sea Level, Horsepower vs Engine Speed

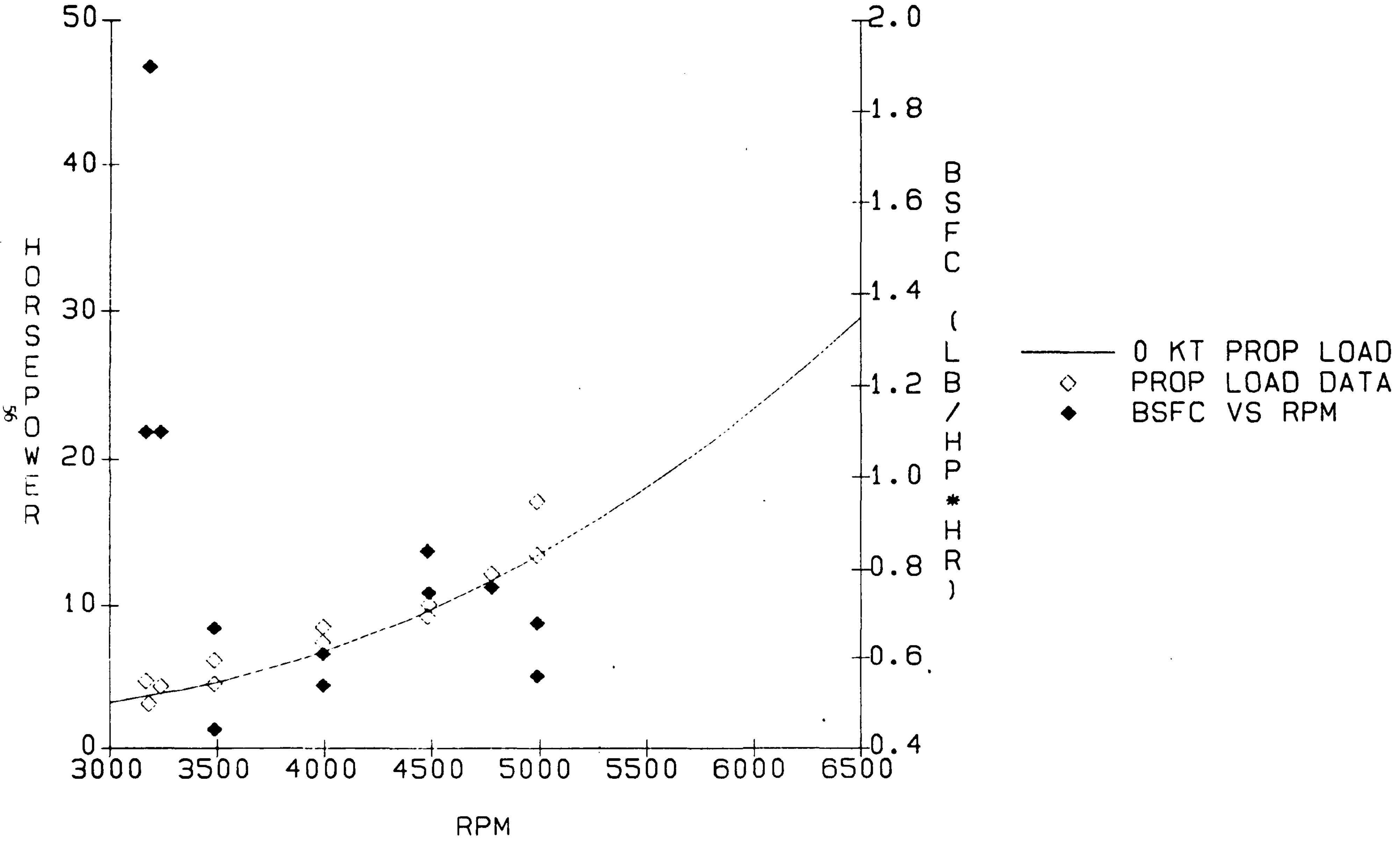


FIGURE 14. AAI HFE S/N 0101-6; 8:1 Compression Ratio Rotor, 7500 Feet, Performance vs RPM

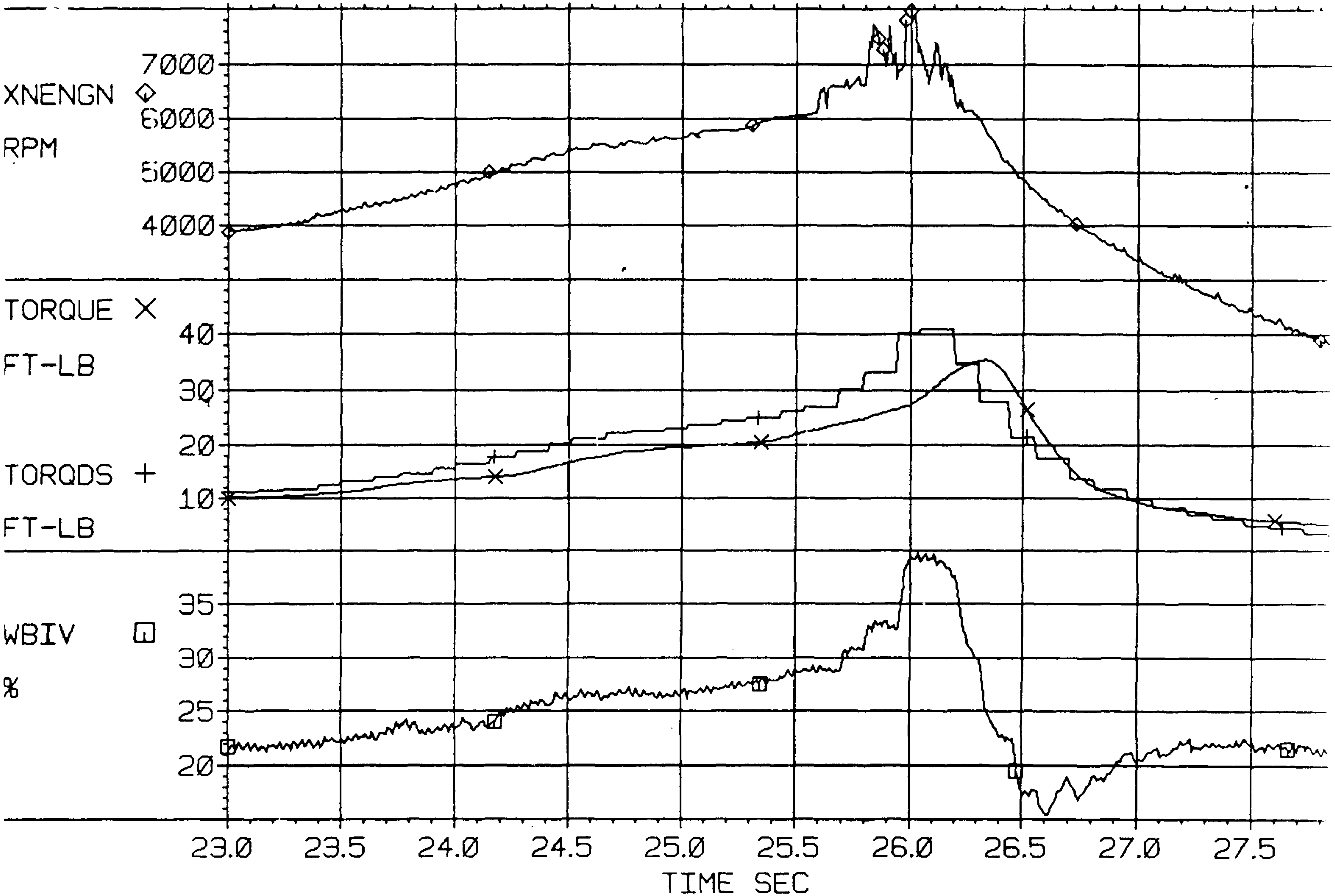


FIGURE 15. AAI HFE S/N 0101-3; Transient Response, Sea Level, Standard Day, Engine Operation on a Propeller Load Curve

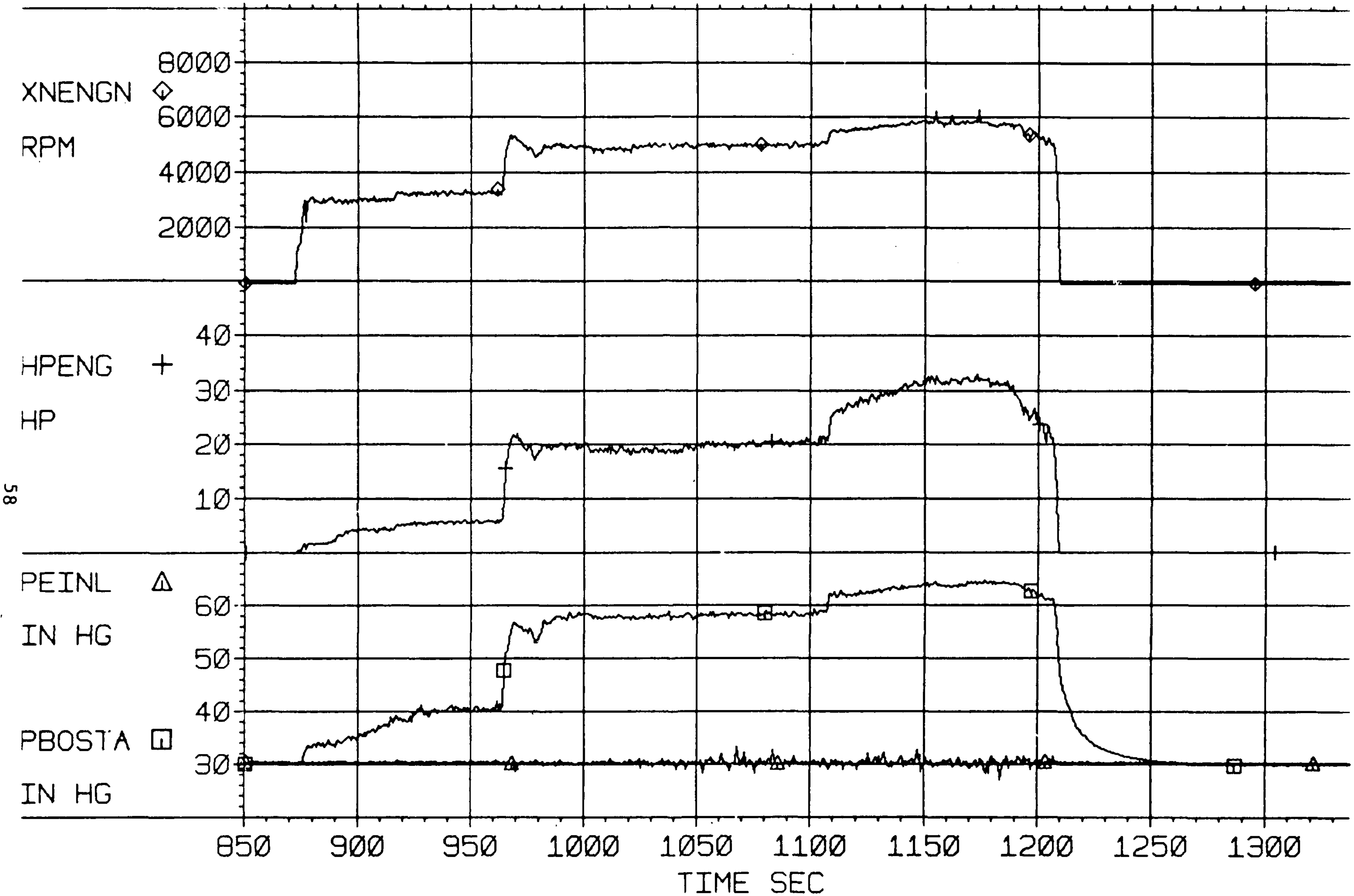


FIGURE 16. AAI HFE S/N 0101-6; Transient Response, Sea Level, Standard Day, of Manifold Inlet Pressure, Engine Speed and Horsepower

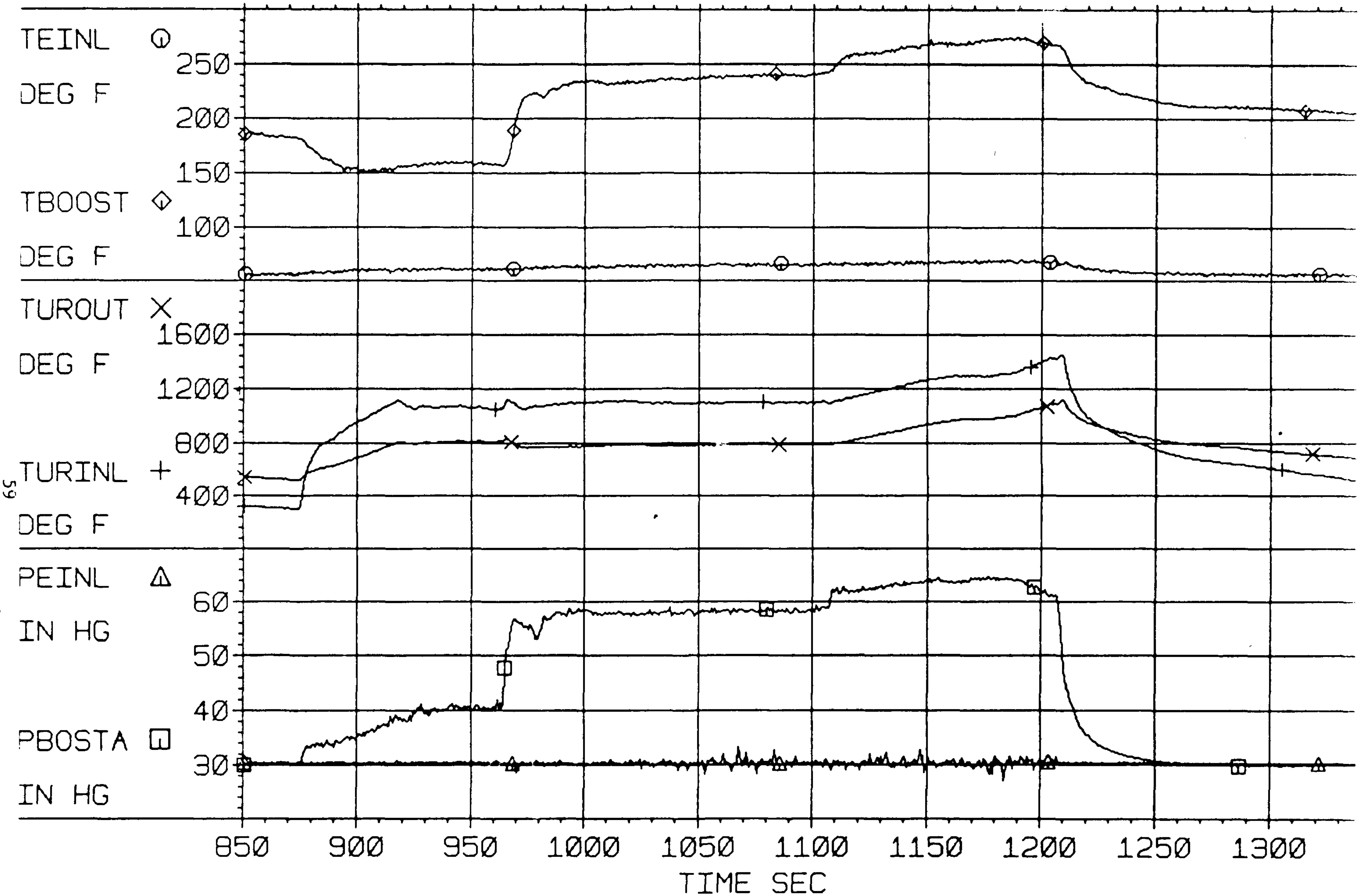


FIGURE 17. AAI HFE S/N 0101-6; Transient Response, Sea Level, Standard Day, of Manifold Inlet Pressure, and Turbine Inlet Temperature

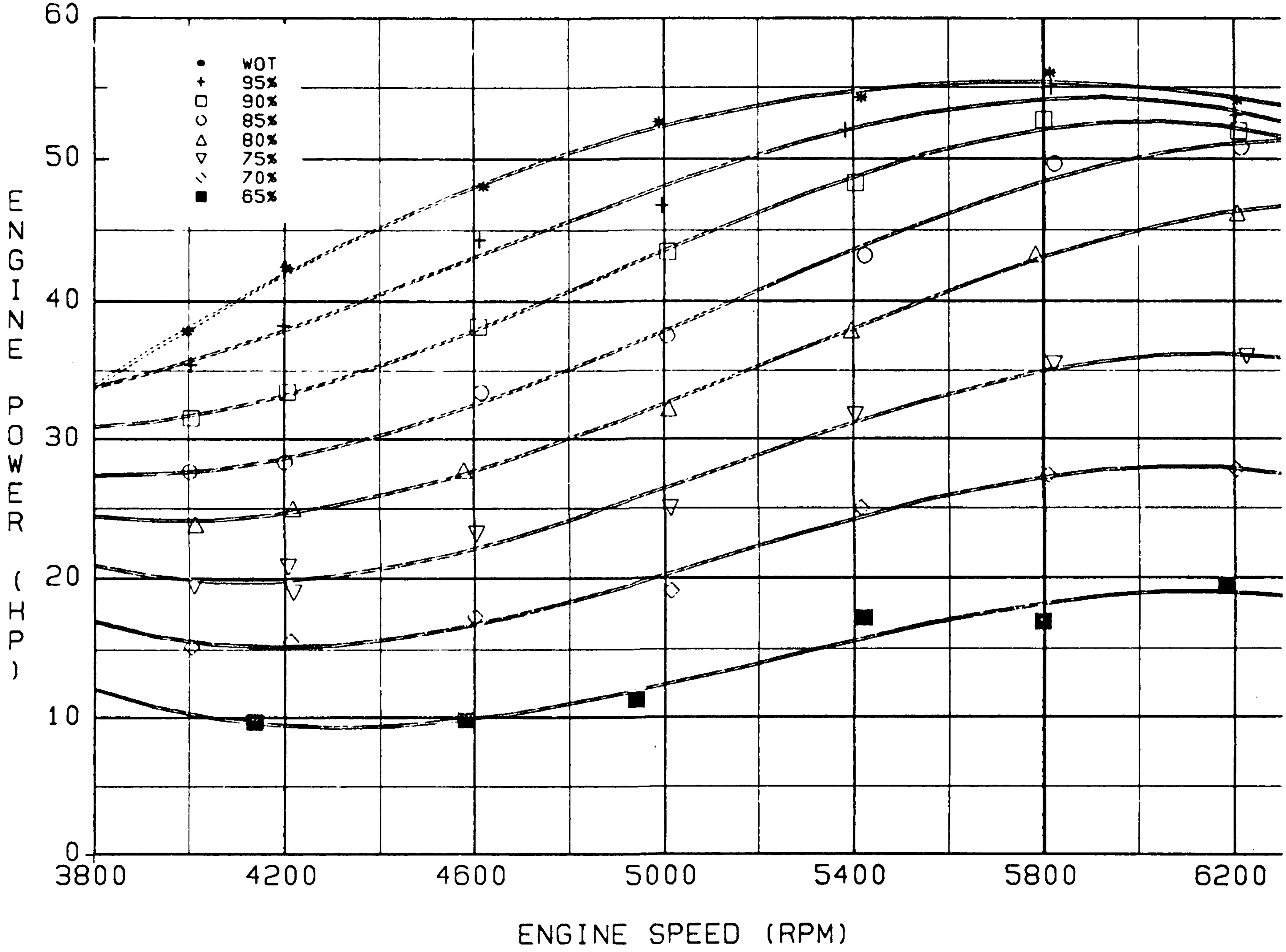


FIGURE 18. DGII HFE; Sea Level, Standard Day, Horsepower vs Engine Speed

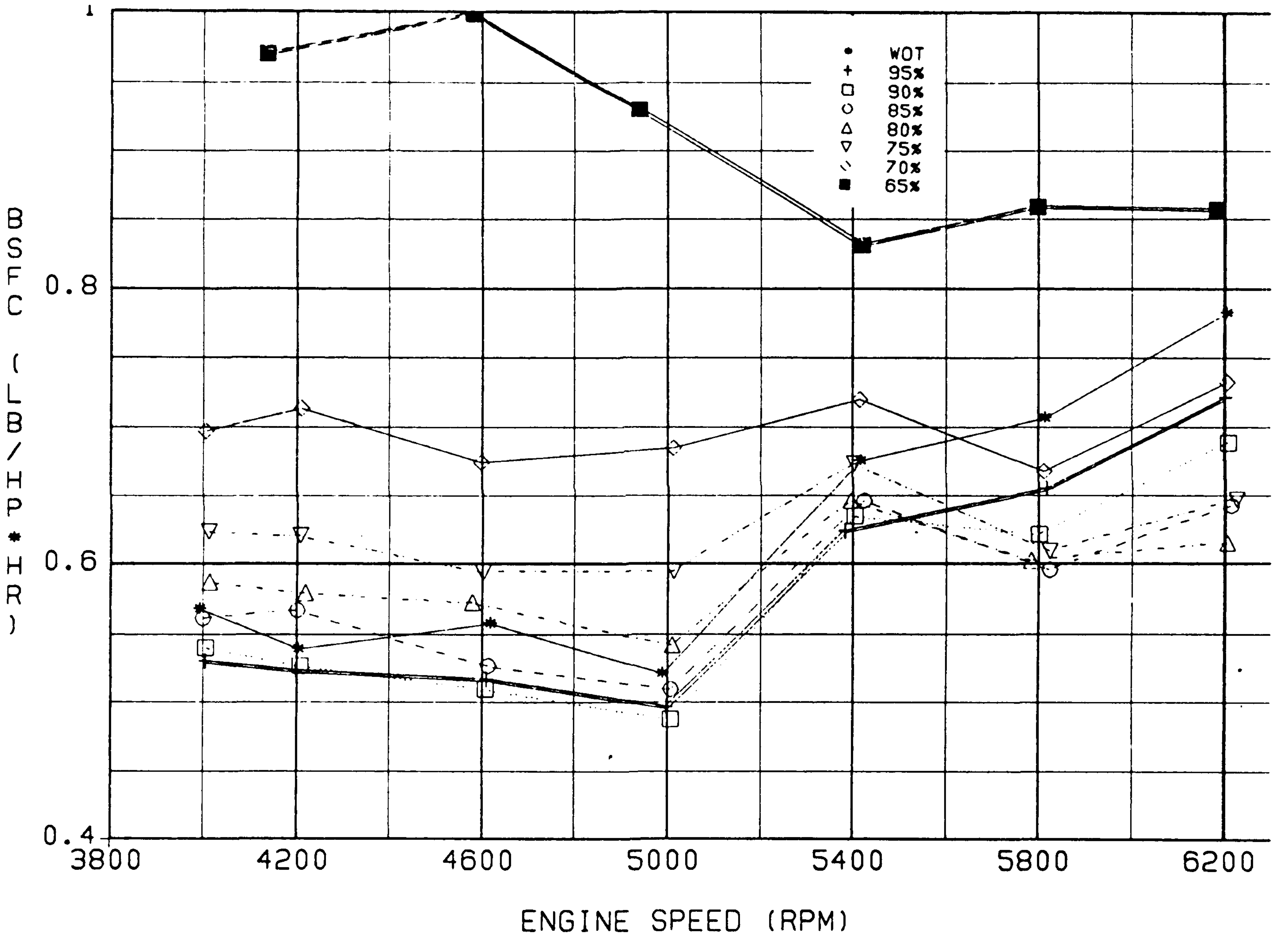


FIGURE 19. DGII HFE; Sea Level, Standard Day, Brake Specific Fuel Consumption vs Engine Speed

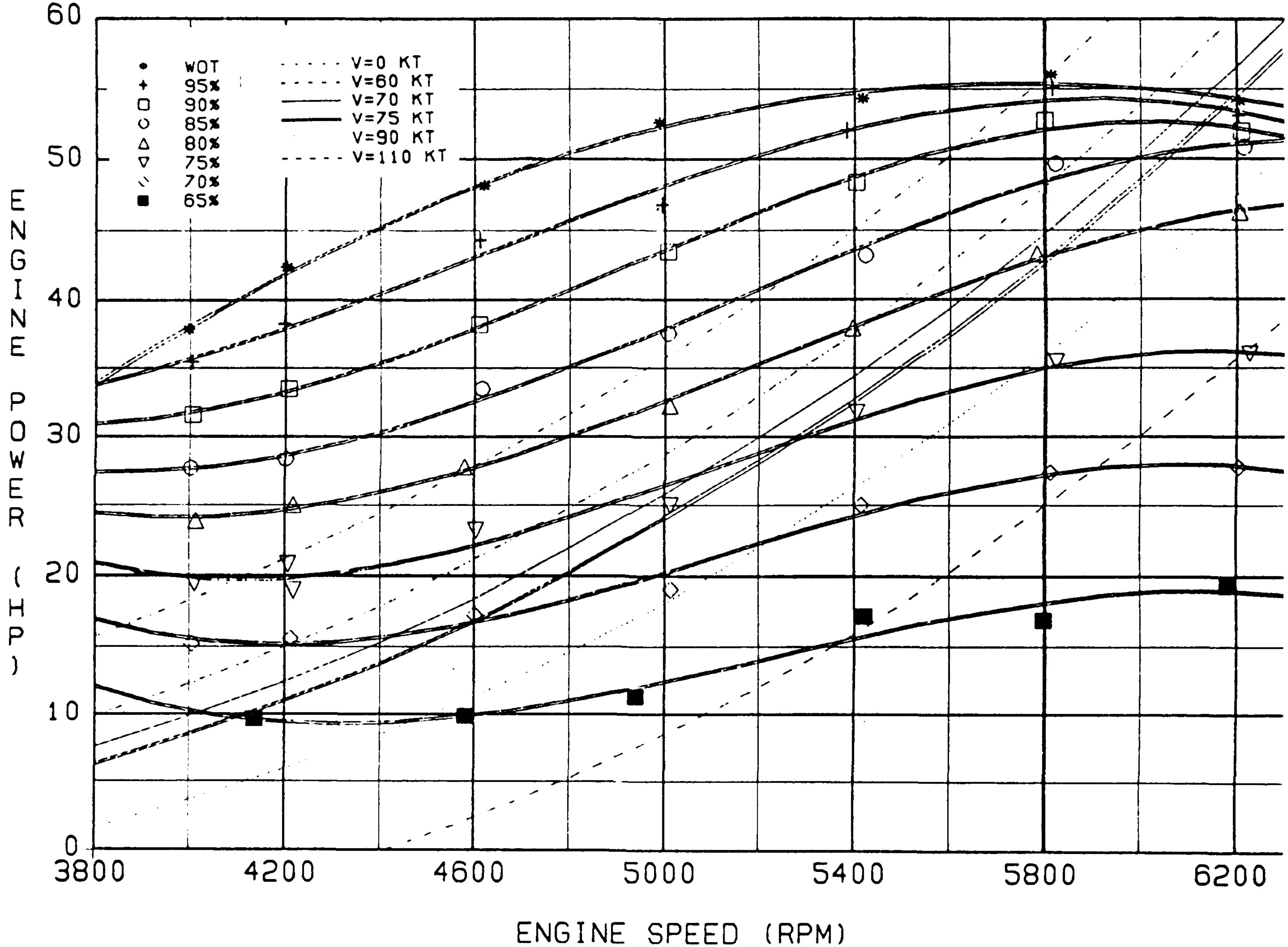


FIGURE 20. DGII HFE; Sea Level, Standard Day, Calibration Data, Simulated Propeller Load Curve Overlay

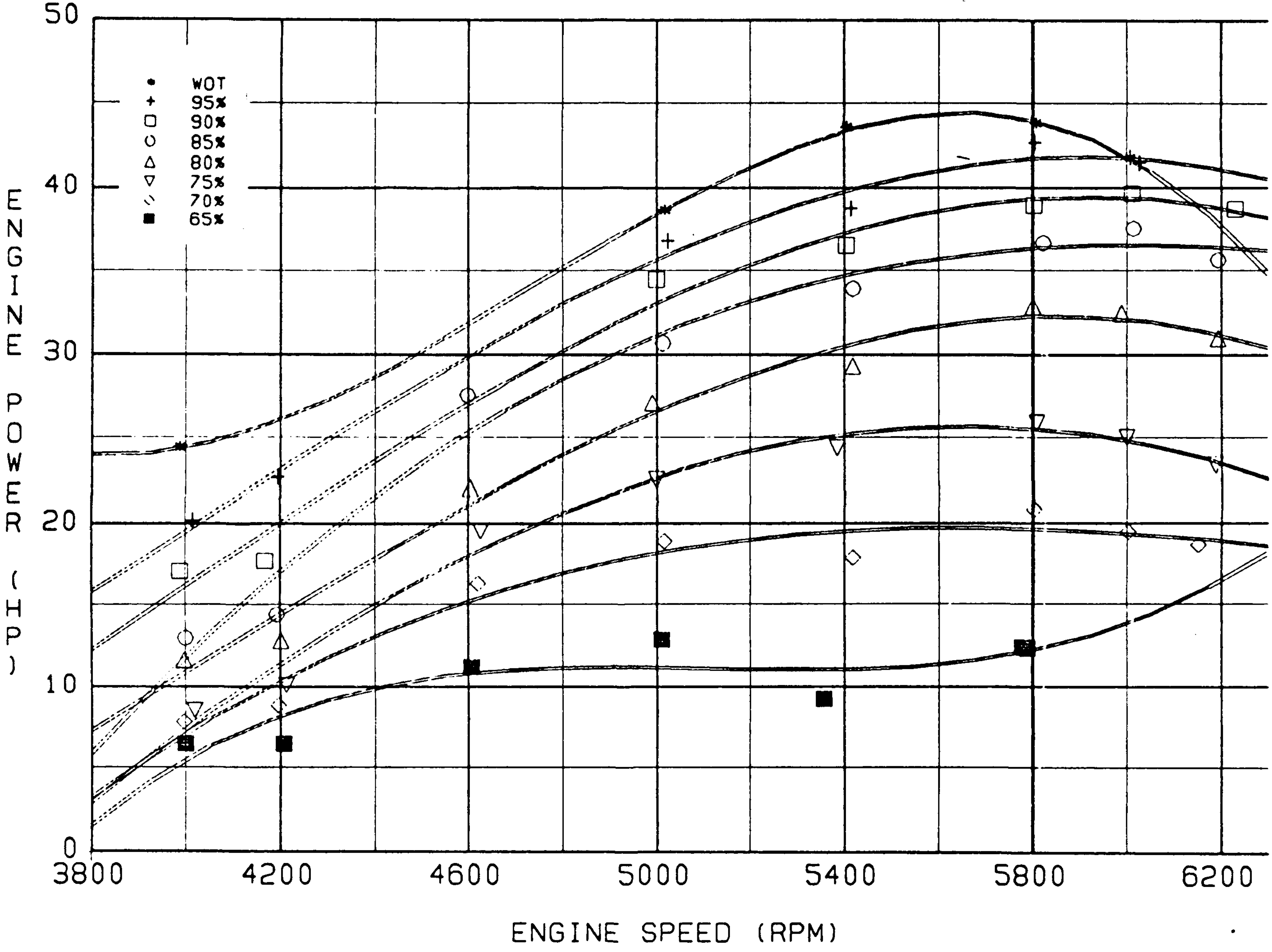


FIGURE 21. DGII HFE; 15000 Feet, Standard Day, Horsepower vs Engine Speed

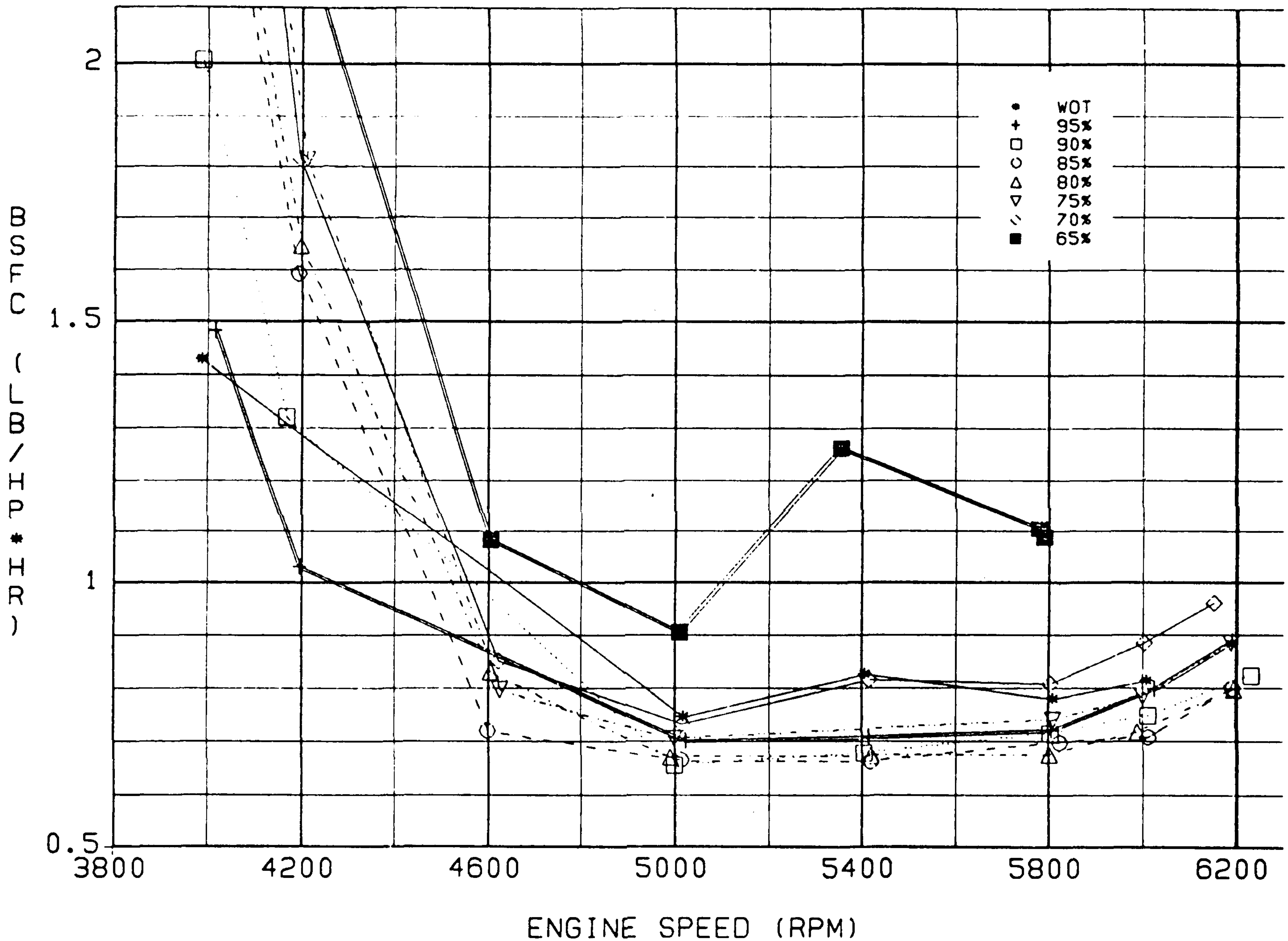


FIGURE 22. DGII HFE; 15000 Feet, Standard Day, Brake Specific Fuel Consumption vs Engine Speed

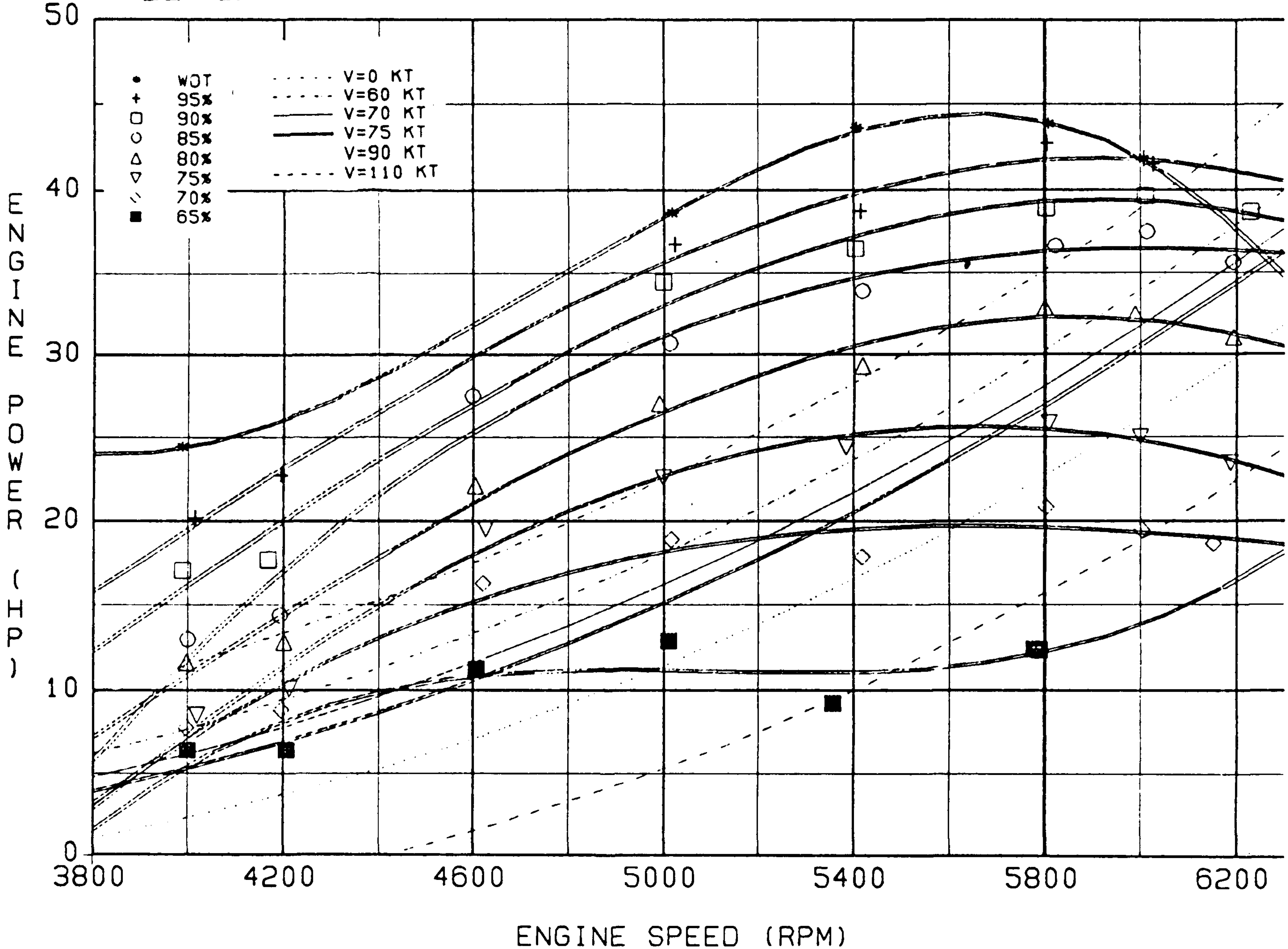


FIGURE 23. DGII HFE; 15000 Feet, Standard Day, Calibration Data, Simulated Propeller Load Curve Overlay

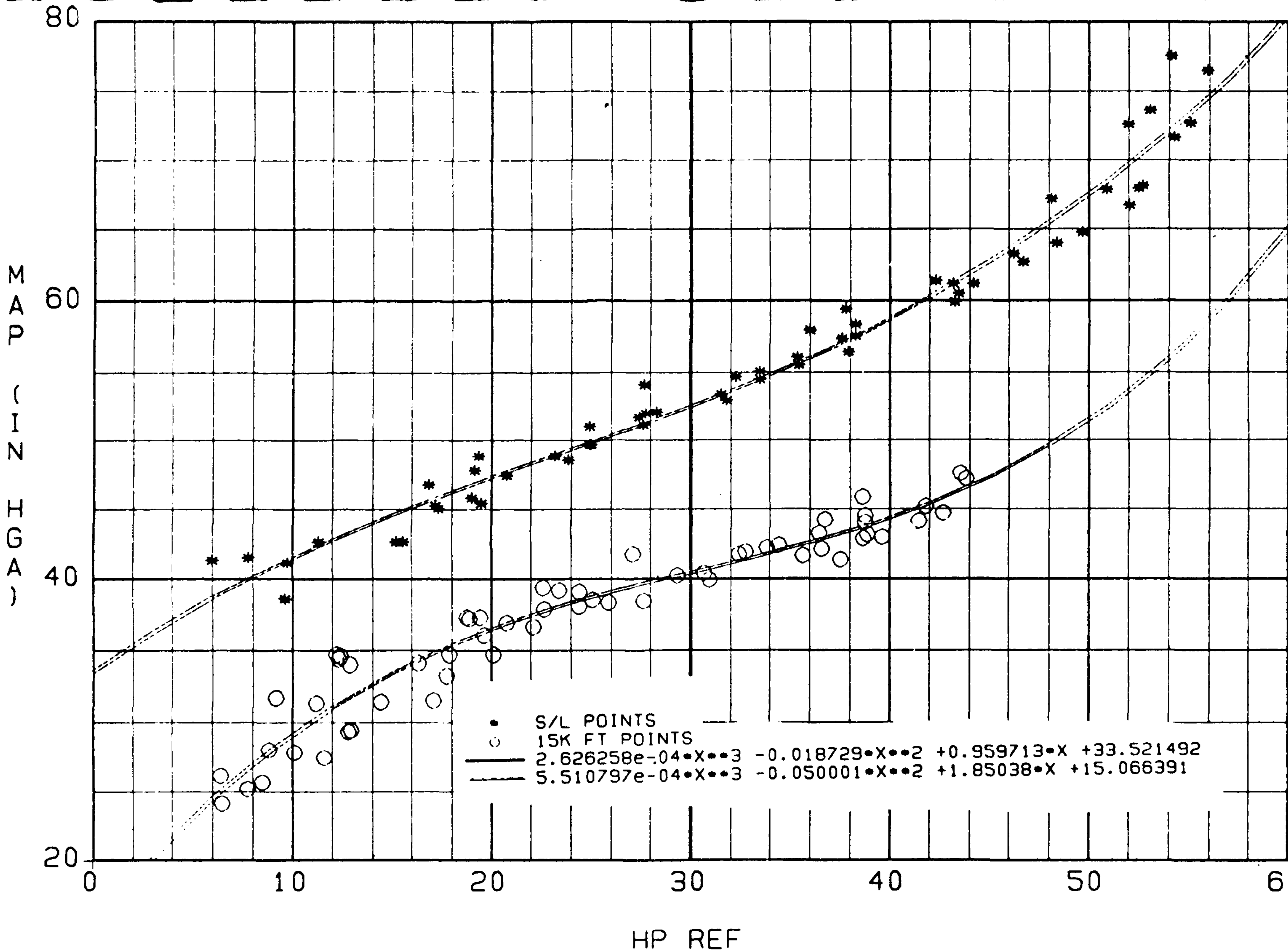


FIGURE 24. DGII HFE; Manifold Pressure vs Referred Horsepower

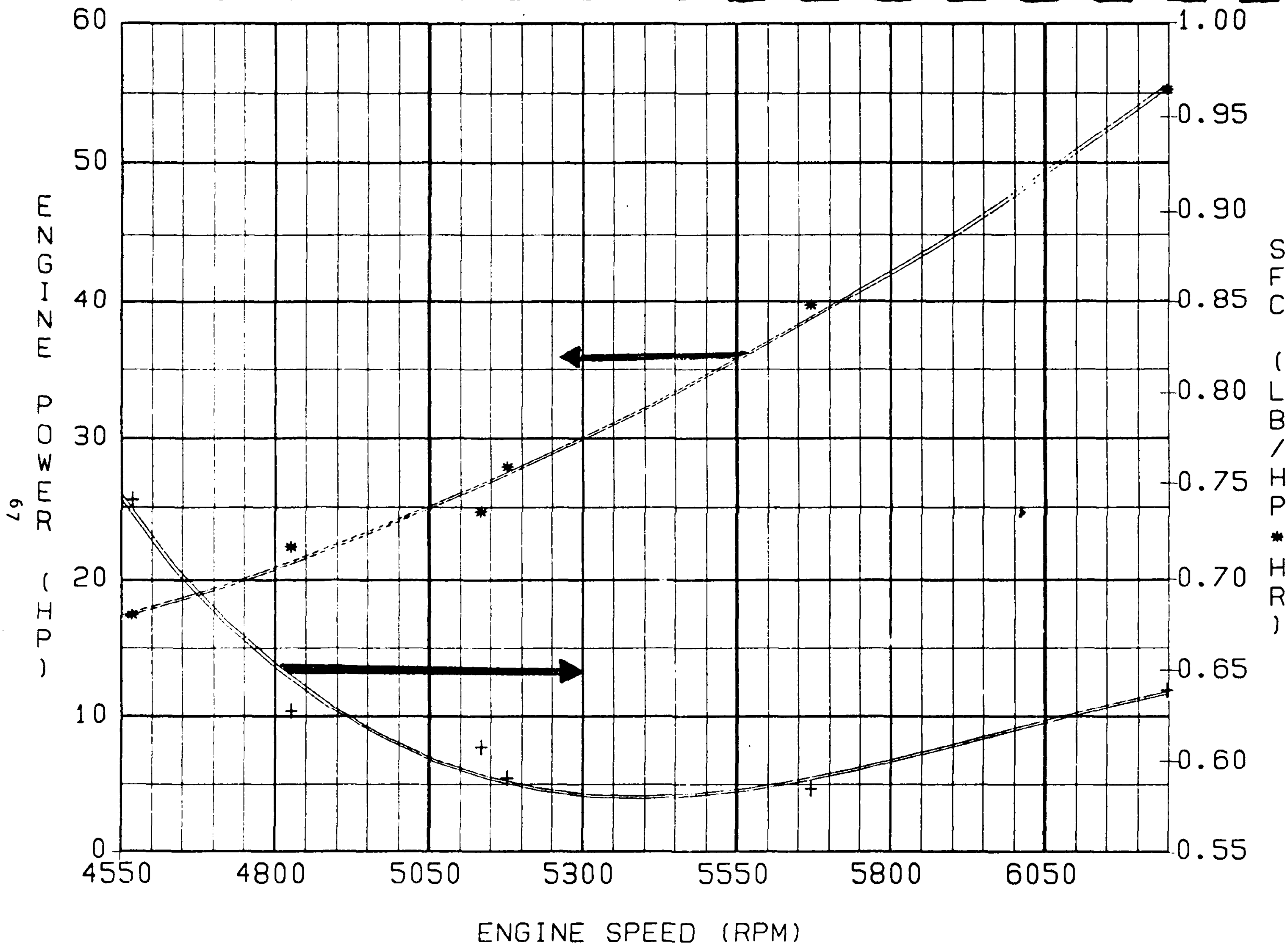


FIGURE 25. DGII HFE; Steady State Propeller Load Performance

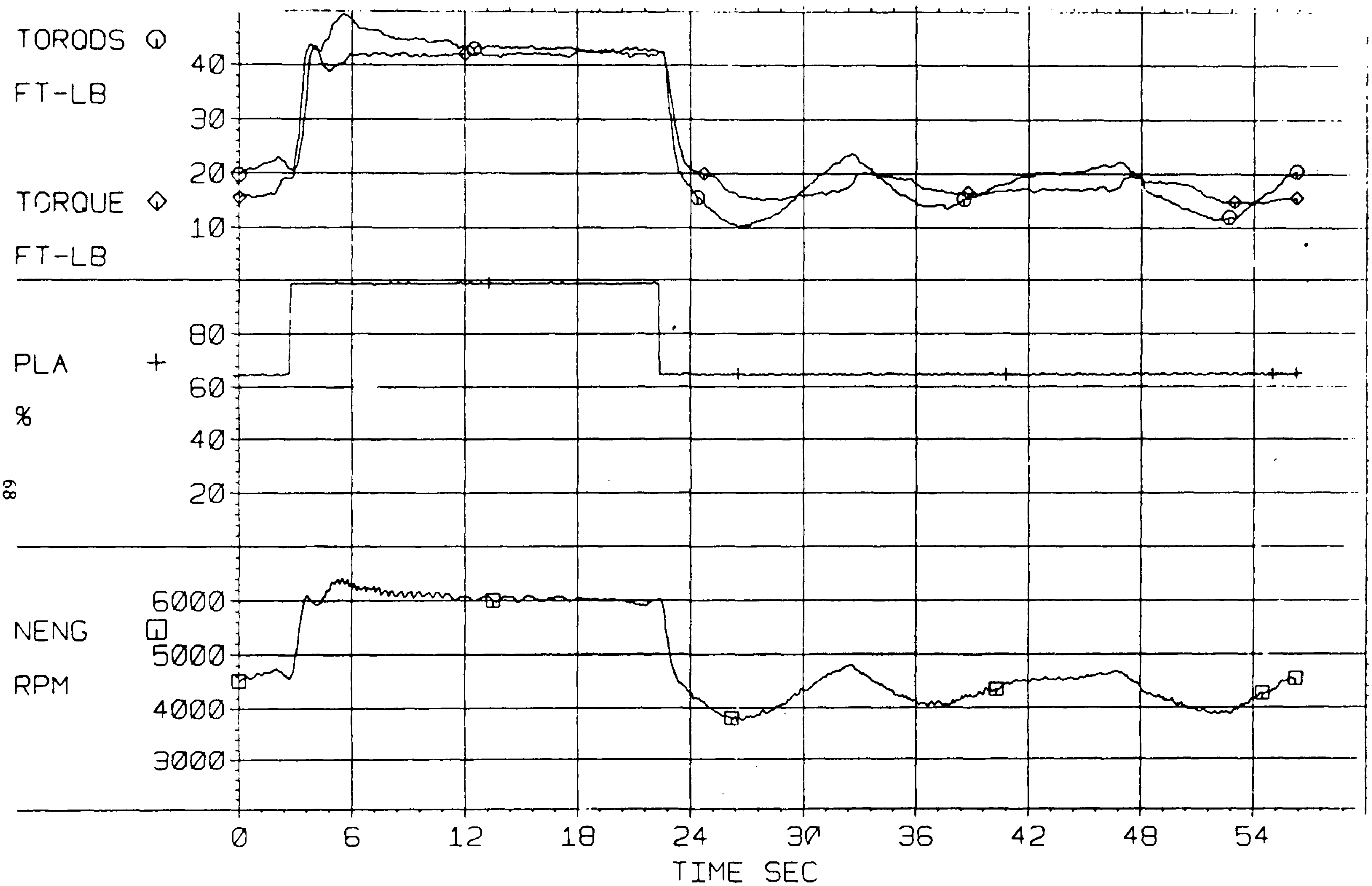


FIGURE 26a. DGII HFE; Transient Response, 70 Knots, Sea Level, Standard Day, Engine Operation on a Propeller Load Curve

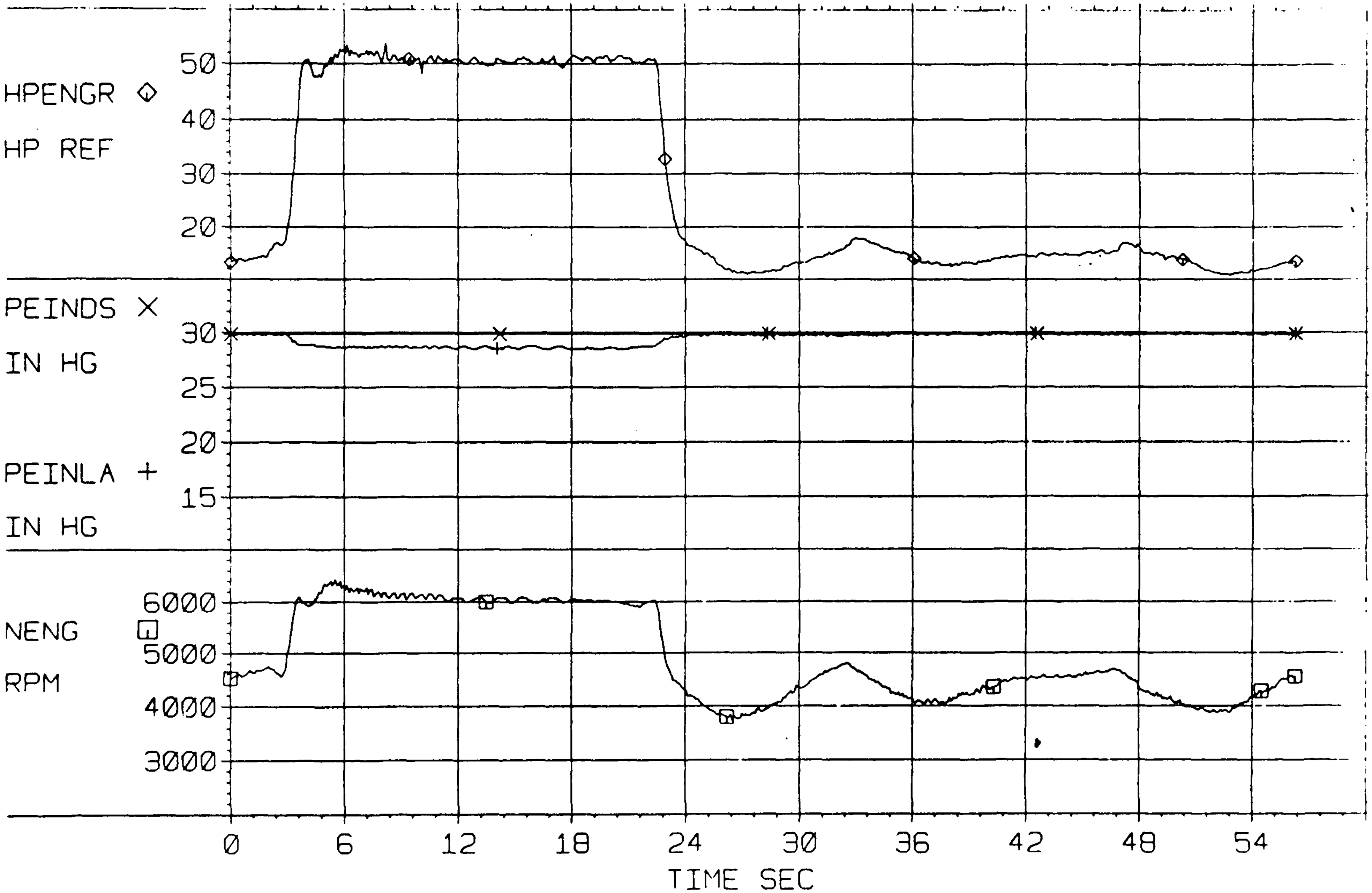


FIGURE 26b. DGII HFE; Transient Response, 70 Knots, Sea Level, Standard Day, Engine Operation on a Propeller Load Curve

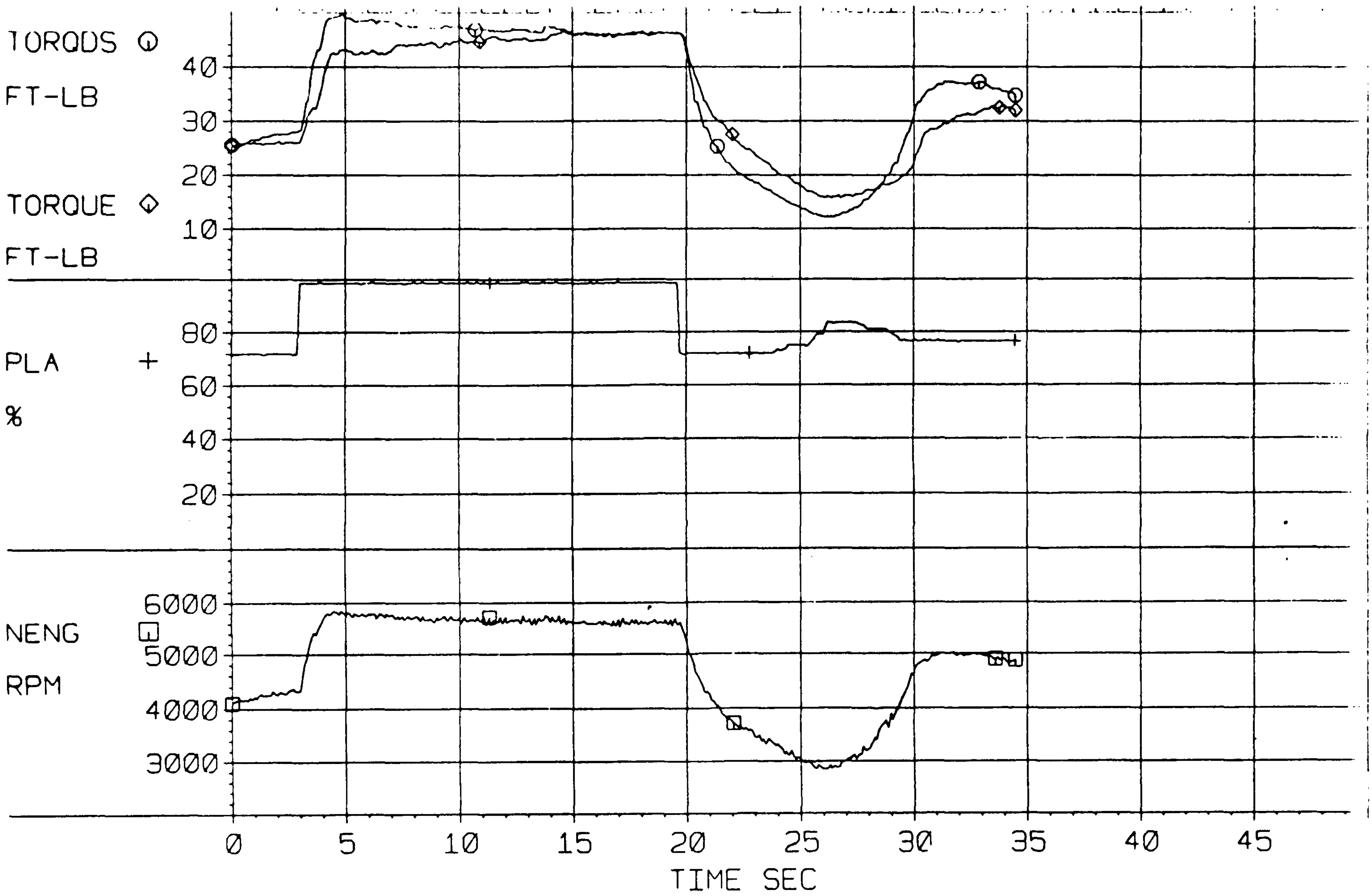


FIGURE 27a. DGII HFE; Transient Response, 0 Knots, Sea Level, Standard Day, Engine Operation on a Propeller Load Curve

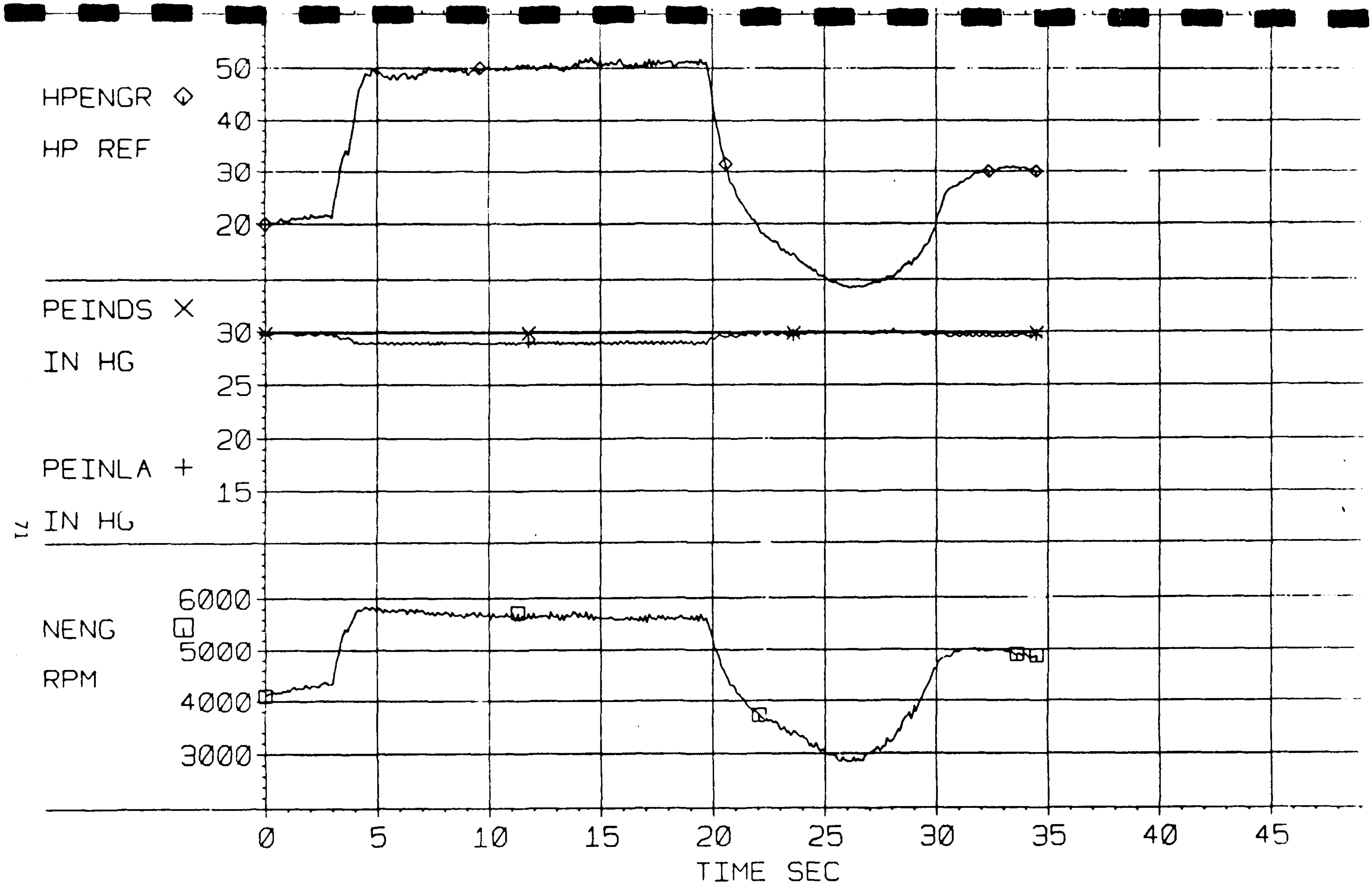


FIGURE 27b. DGII HFE; Transient Response, 0 Knots, Sea Level, Standard Day, Engine Operation on a Propeller Load Curve

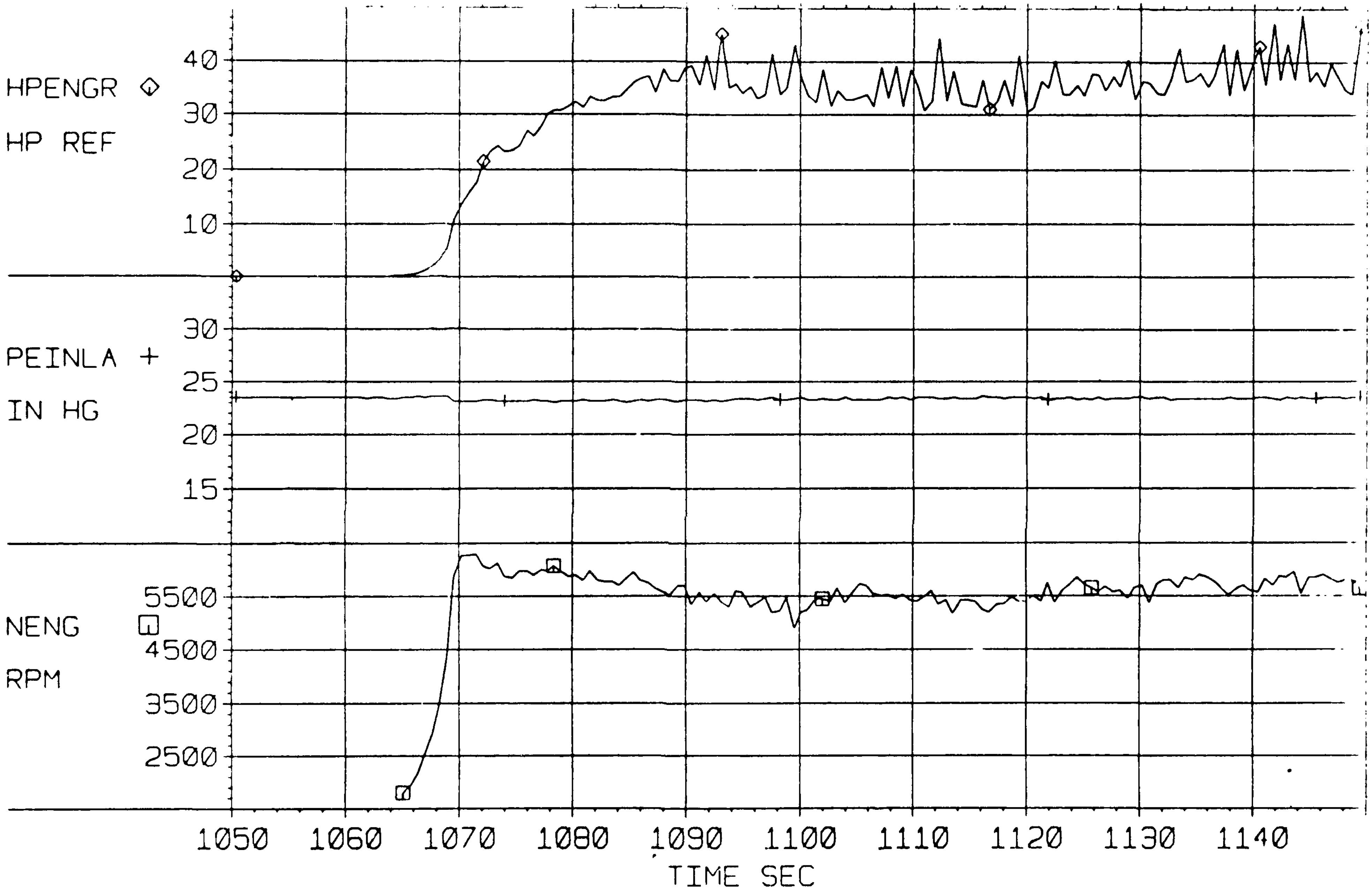


FIGURE 28a. DGII HFE; Transient Response, 15000 Feet, Standard Day, Engine Altitude Start

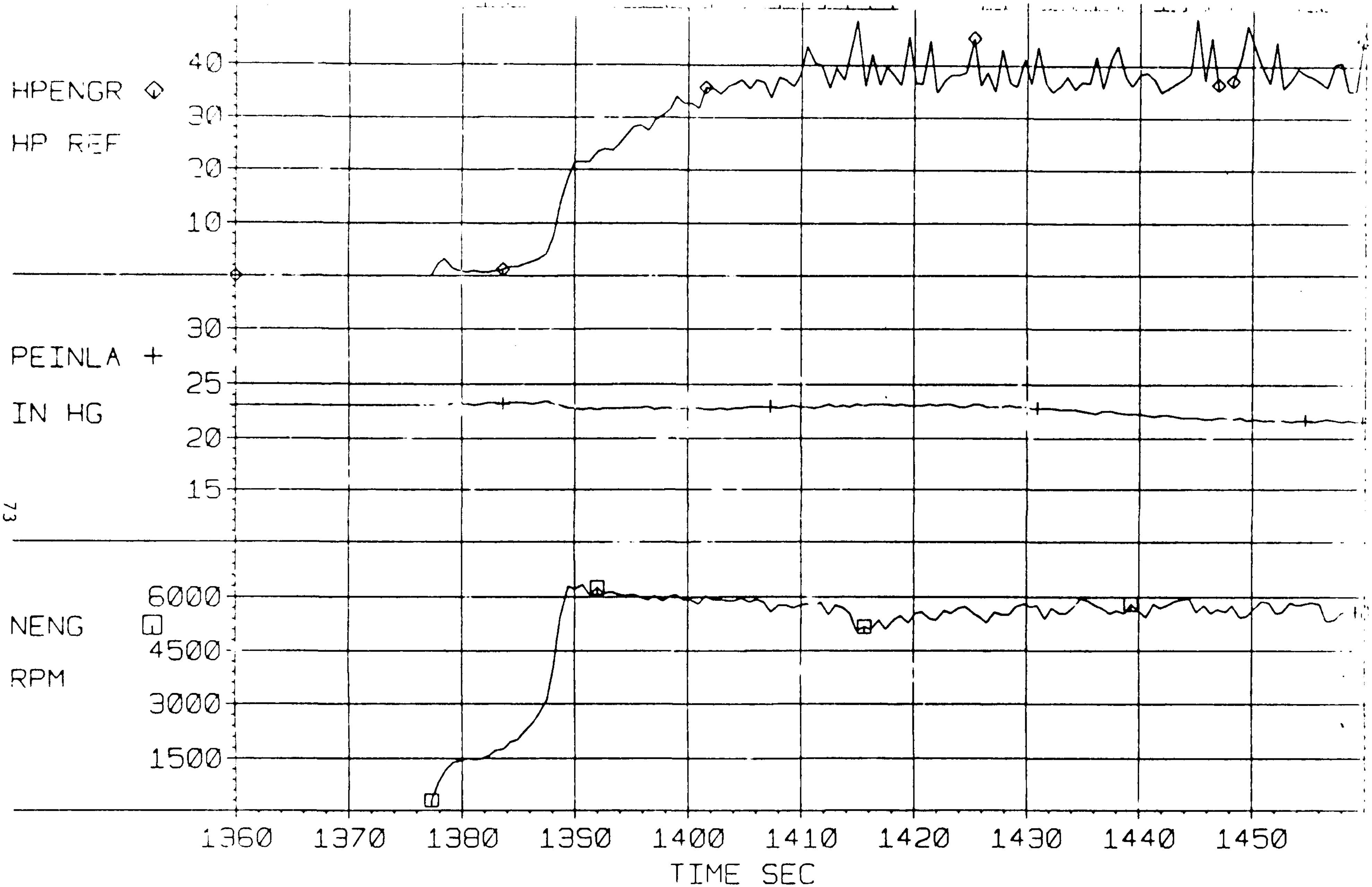


FIGURE 28b. DGII HFE; Transient Response, 15000 Feet, Standard Day, Engine Altitude Start

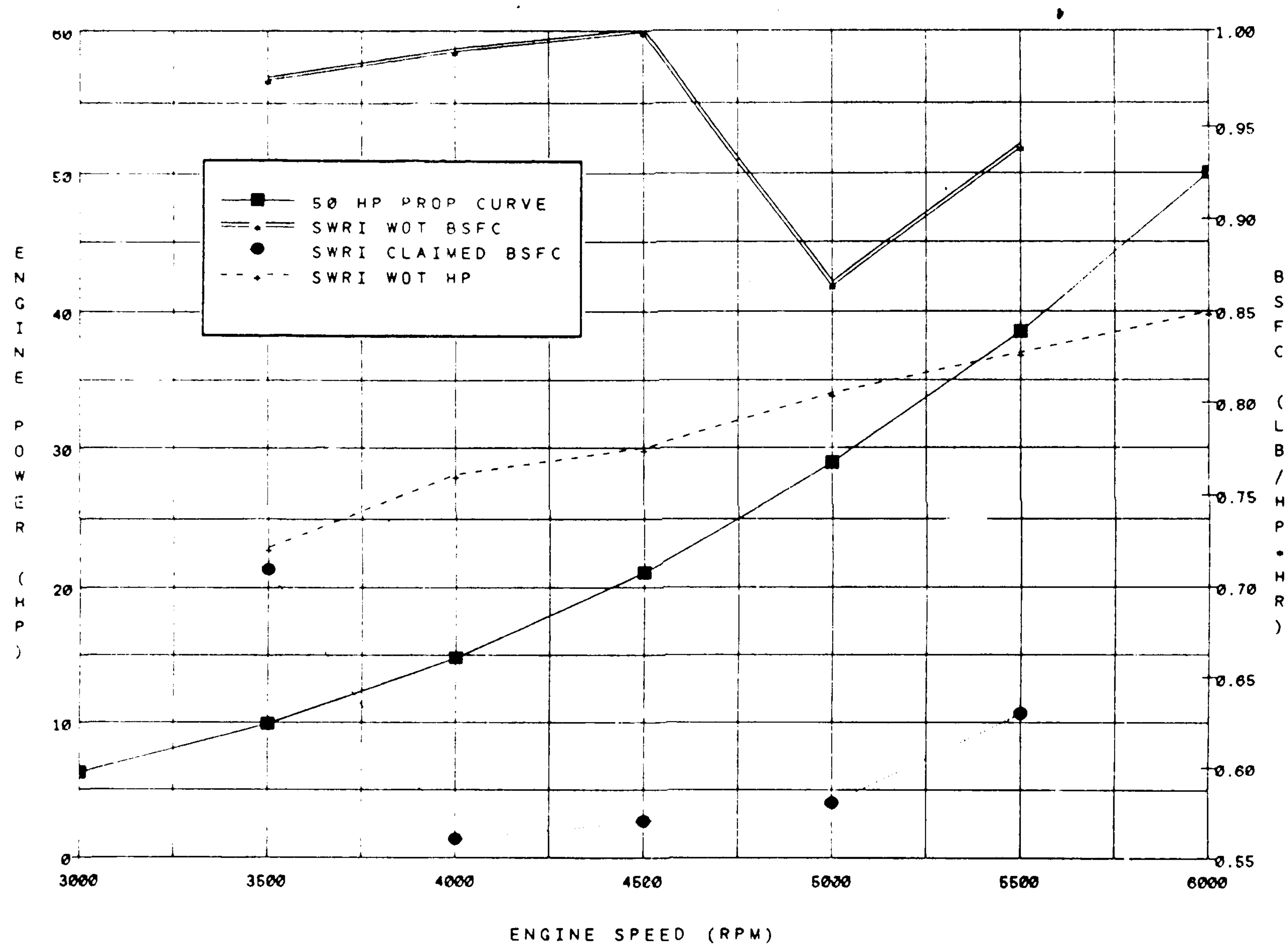


FIGURE 29. SwRI HFE; Baseline Engine Performance Demonstrated by SwRI

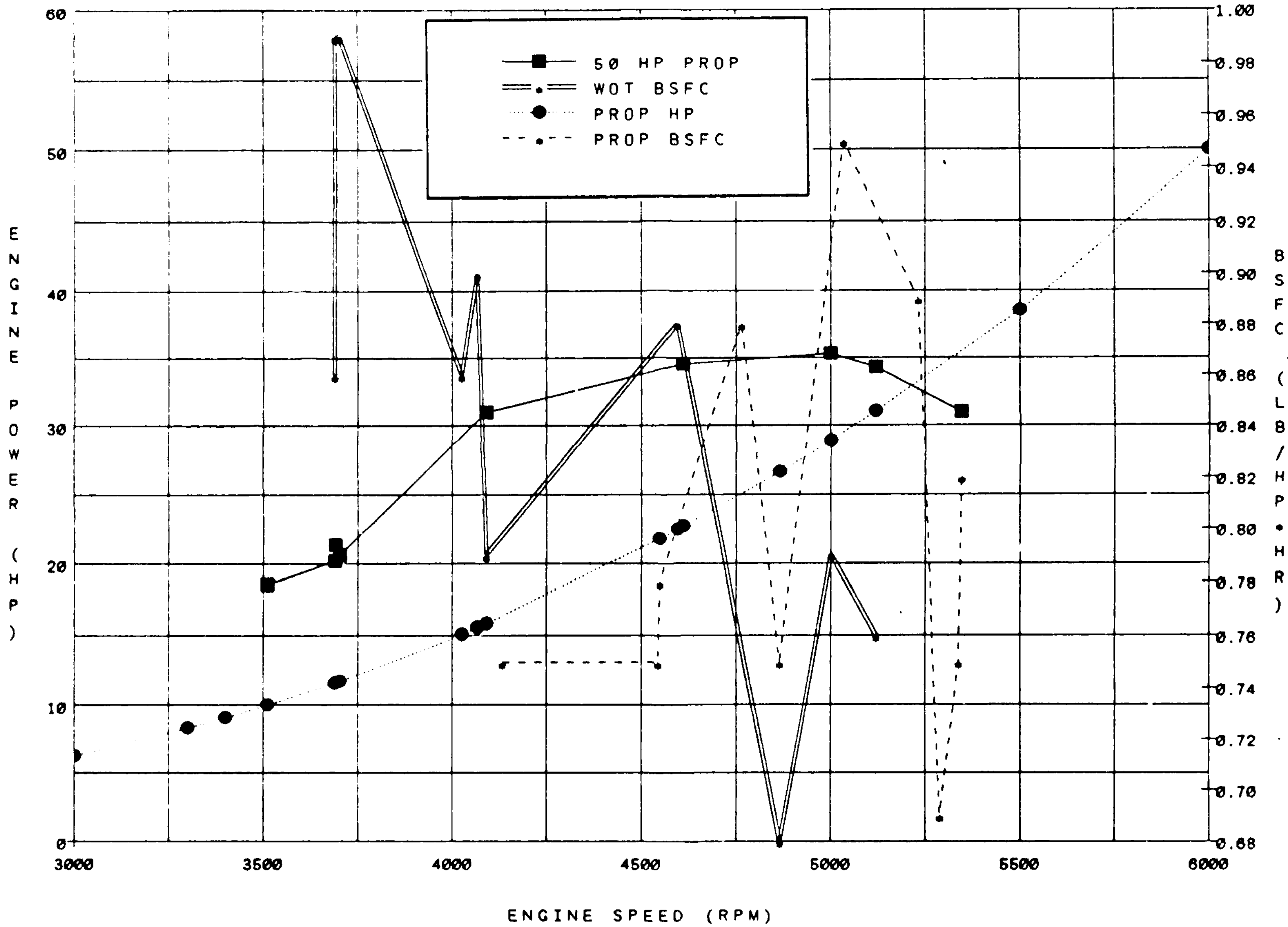


FIGURE 30. SwRI HFE; Actual Baseline Performance Demonstrated at NAVAIRWARCENACDIVTRN

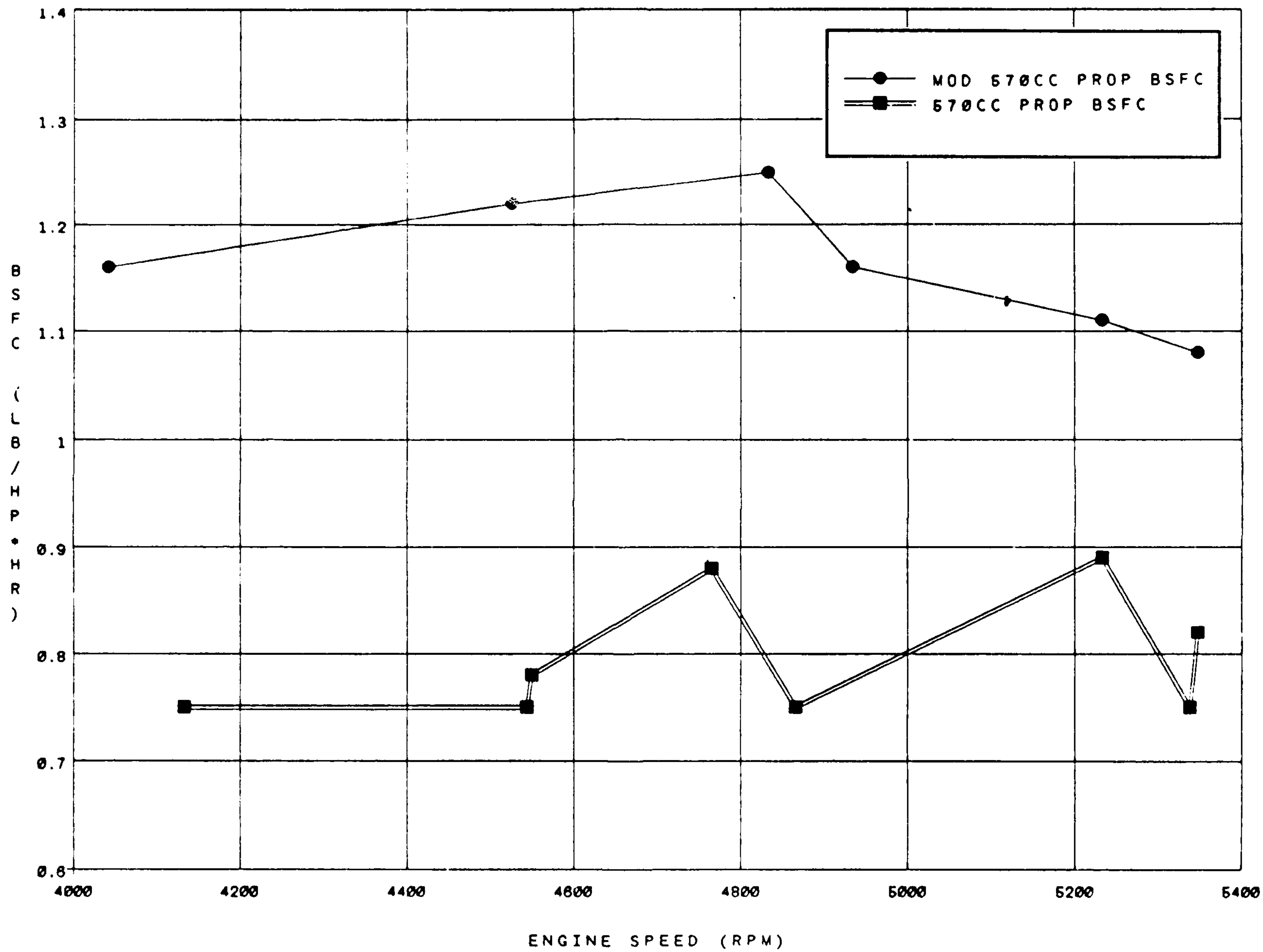


FIGURE 31. SwRI HFE; 570 cc and Modified 570 cc Exhaust System BSFC Data Operating on 50 HP Propeller Load Curve

TABLE 1

HOT START TEST AND OPERATIONAL MISSION USING JP-8 FUEL

MODE	ALT (kFT)	TAMB (°F)	PAMB (in.hg)	TAS (KTS)	PLA	TIME (MIN)	MISSION CLOCK
Climb	0 - 15	103 - 45	29.92 - 16.89	70	MAX	20.0	0:20:00
Cruise	15	45	16.89	90	TBD	30.0	0:50:00
Dash	15	45	16.89	110	MAX	10.0	1:00:00
Descent	15 - 1	45 - 99	16.89 - 28.86	75	IDLE	20.0	1:20:00
Loiter	1	99	28.86	60	TBD	39:50	1:59:50
*** SUSPEND MISSION TO CHANGE PLANT TO COLD CONDITIONS ***							
Loiter	1	-25	28.86	60	TBD	10 sec	2:00:00
Climb	1 - 15	-25	28.86 - 16.89	70	MAX	20.0	2:20:00
Cruise	15	-25	16.89	90	TBD	30.0	2:50:00
Dash	15	-25	16.89	110	MAX	10.0	3:00:00
Descent	15 - 1	-25	16.89 - 28.86	75	IDLE	20.0	3:20:00
Loiter	1	-25	28.86	60	TBD	40.0	4:00:00

TABLE 2

COLD START TEST AND OPERATIONAL MISSION USING JP-5 FUEL

MODE	ALT (kFT)	TAMB (°F)	PAMB (in.hg)	TAS (KTS)	PLA	TIME (MIN)	MISSION CLOCK
Climb	0 - 15	-25	29.92 - 16.89	70	MAX	20.0	0:20:00
Cruise	15	-25	16.89	90	TBD	30.0	0:50:00
Dash	15	-25	16.89	110	MAX	10.0	1:00:00
Descent	15 - 1	-25	16.89 - 28.86	75	IDLE	20.0	1:20:00
Loiter	1	-25	28.86	60	TBD	39:50	1:59:50
*** SUSPEND MISSION TO CHANGE PLANT TO HOT CONDITIONS ***							
Loiter	1	99	28.86	60	TBD	10 sec	2:00:00
Climb	1 - 15	99 - 45	28.86 - 16.89	70	MAX	20.0	2:20:00
Cruise	15	45	16.89	90	TBD	30.0	2:50:00
Dash	15	45	16.89	110	MAX	10.0	3:00:00
Descent	15 - 1	45 - 99	16.89 - 28.86	75	IDLE	20.0	3:20:00
Loiter	1	99	28.86	60	TBD	40.0	4:00:00

TABLE 3

STANDARD DAY START TEST AND OPERATIONAL MISSION USING DIESEL FUEL

MODE	ALT (kFT)	TAMB (°F)	PAMB (in.hg)	TAS (KTS)	PLA	TIME (MIN)	MISSION CLOCK
Climb	0 - 15	59 - 6	29.92 - 16.89	70	MAX	20.0	0:20:00
Cruise	15	6	16.89	90	TBD	30.0	0:50:00
Dash	15	6	16.89	110	MAX	10.0	1:00:00
Descent	15 - 1	6 - 55	16.89 - 28.86	75	IDLE	20.0	1:20:00
Loiter	1	55	28.86	60	TBD	39:50	1:59:50
*** SUSPEND MISSION TO CHANGE PLANT TO HOT CONDITIONS ***							
Loiter	1	99	28.86	60	TBD	10 sec	2:00:00
Climb	1 - 15	99 - 45	28.86 - 16.89	70	MAX	20.0	2:20:00
Cruise	15	45	16.89	90	TBD	30.0	2:50:00
Dash	15	45	16.89	110	MAX	10.0	3:00:00
Descent	15 - 1	45 - 99	16.89 - 28.86	75	IDLE	20.0	3:20:00
Loiter	1	99	28.86	60	TBD	40.0	4:00:00

TABLE 4

TRAINING MISSION SIMULATION

MODE	ALT (kFT)	TAMB (°F)	PAMB (in.hg)	TAS (KTS)	PLA	TIME (MIN)	MISSION CLOCK
Climb	0 - 2	59 - 52	29.92 - 27.82	70	MAX	4.0	0:04:00
Cruise	2	52	27.82	90	TBD	4.0	0:08:00
Descent	2 - 0	52 - 59	27.82 - 29.92	70	IDLE	4.0	0:12:00

TABLE 5

DGII ENGINE CALIBRATION CONDITIONS

ALTITUDE (ft)	TAMB (+/-2°F)	PAMB (+/-0.1 in.hg)	FUEL TYPE
Sea Level	125.0	29.92	JP-5
Sea Level	59.0	29.92	JP-5
5000	41.2	24.90	JP-5
10000	23.3	20.58	JP-5
15000	5.5	16.89	JP-5
Sea Level	0.0	29.92	JP-5
Sea Level	59.0	29.92	Diesel

TABLE 6

AAI HFE Serial Numbers and Test Dates

DATES INSTALLED IN 6W	ENGINE SERIAL NUMBER	ENGINE BUILD NUMBER	COMPRESSION RATIO
17 APR 92 - 21 APR 92	0102	0	8.8:1.0
23 APR 92 - 25 APR 92	0101	0	8.8:1.0
04 MAY 92 - 07 MAY 92	0101	1	8.0:1.0
12 MAY 92 - 13 MAY 92	0102	1	8.8:1.0
19 MAY 92 - 20 MAY 92	0101	2	8.0:1.0
09 NOV 92 - 13 NOV 92	0101	3	8.0:1.0
20 NOV 92 - 23 NOV 92	0101	4	8.8:1.0
18 DEC 92 - 30 DEC 92	0101	5	8.0:1.0
15 JAN 93 - 22 JAN 93	0101	6	8.0:1.0

TABLE 7

DGI HFE OIL ANALYSIS

SAMPLE #	DATE	ENGINE S/N	Fe	Ag	Al	Cr	Cu	Mg	Ni	Pb	Si	Sn	Ti	ENGINE TIME	OIL TIME
851	4 NOV 92	DGI-HFE 038	2.6	0	1.1	0	0	400	0	0	4.1	0	0	0	0
836	9 OCT 92	DGI-HFE 038	3.0	0	3	0	7	537	1	0	9	0	0	20.468	20.468
830	14 OCT 92	DGI-HFE 038	113	0	55	2	14	481	0	0	13	13	0	25.668	5.200
831	15 OCT 92	DGI-HFE 038	70	0	29	0	7	461	0	0	8	2	0	26.385	0.767

TABLE 8

AAI Achievement of HFE Goals

Goal	Demonstrated	Assessed Potential
50 HP	32.0 HP	44.0 HP*
BSFC (lb/HP-hr)	0.42	-
50 lb Maximum Weight (lbs)	71.0	65.0*
7500 ft Start	Successful*	-
0 to 15k ft Operation	Sea level to 7500 ft	Achievable*
-25°F to 125°F Operation	44.0°F to 125.0°F	Achievable*
300 hr Durability	11.50	Achievable*
Multi-Fuel Operation	JP-5	JP-5, JP-8, Diesel*

* Please refer to section 4.3.1 for rationale

TABLE 9

DGII Achievement of HFE Goals

Goal	Demonstrated	Assessed Potential
50 HP	56.0 HP	56.0 HP
BSFC (lb/HP-hr)	0.52	0.5*
50 lb Maximum Weight (lbs)	102.0	80.0*
7500 ft Start	Successful	-
0 to 15k ft Operation	Successful	-
-25°F to 125°F Operation	26.0°F to 76.0°F	Achievable*
300 hr Durability	33.385	Achievable*
Multi-Fuel Operation	JP-5	JP-5, JP-8, Diesel*

* Please refer to section 4.3.2 for rationale

TABLE 10

SwRI Achievement of HFE Goals

Goal	Demonstrated	Assessed Potential
50 HP	35.3 HP	50.0 HP*
BSFC (lb/HP-hr)	0.69	0.5*
50 lb Maximum Weight (lbs)	50.0	-
7500 ft Start	Not Tested	Achievable*
0 to 15k ft Operation	Sea level only	Achievable*
-25°F to 125°F Operation	54.0°F to 112.2°F	Achievable*
300 hr Durability	14 hrs (core engine)	Achievable*
Multi-Fuel Operation	JP-5	JP-5, JP-8, Diesel*

* Please refer to section 4.3.3 for rationale

Appendix A

Instrumentation List for AAI HFE Test

APPENDIX A

INSTRUMENTATION REQUIREMENTS FOR AAI WFE TEST

TEMPERATURES

	PARAMETER			DESIRED				GUAGES		OPERATING		
SYMBOL	DESCRIPTION	QTY	RANGE F	ACCURACY	RTM	SS	TRANS	DED	SWITCH	LIMIT	ALARM	REMARKS
TEINL1	ENGINE INL (MP)	3	-25 TO 200	+/-2F								
TEINL2	" "											
TENIL3	" "											
TEINL	ENGINE AIR INLET	1	-25 TO 200	+/-2F	1	1	1	0	1	130 F		TWIST-WIRE T/C
TBOOST	ENG AIR INLET	1	-50 TO 200	+/-5F	1	1	1	0	1	130 F		PROBE T/C
TEBRG	ENG ROTOR BRG	1	-25 TO 200	+/-2F	1	1	1	0	1	210 F		SKIN T/C
TURINL	TURBO INLET(EXH)	1	-50 TO 2200	+/-10F	1	1	1	1	1	1700 F	1750 F	PROBE T/C
TUROUT	TURBO OUTLET	1	-50 TO 2200	+/-10F	1	1	1	0	1	2000 F		PROBE T/C
TFPUMP	FUEL AT PUMP INL	1	-50 TO 200	+/-2F	1	1	1	1	0	130 F/-25 F		STD T/C
TFTNK	FUEL TANK	1	-50 TO 150	+/-2F	1	1	1	0	0	130 F		STD T/C
TRCLO	ROTOR COOL (AIR)	1	-50 TO 350	+/-2F	1	1	1	1	0	310 F	320 F	STD T/C
TRCLI	ROTOR COOL INL	1	-50 TO 350	+/-2F	1	1	1	0	1	310 F		STD T/C
TENGCL	ENGINE COOLANT	1	-50 TO 300	+/-2F	1	1	1	1	0	210 F	220 F	STD T/C
THEXCH	HEAT EXCHANGER	1	-50 TO 300	+/-2F	1	1	1	1	0	210 F	210 F	STD T/C
TECU	ENG CONTROLLER	1	-50 TO 300	+/-2F	1	1	1	0	1	NC		SKIN T/C
TCELL1	CELL AMBIENT	4	-50 TO 200	+/-5F	0	4	1	1	4	130 F		COORDINATE
TCELL2	" "											LOCATIONS
TCELL3	" "											WITH PE22
TCELL4	" "											
TEAMB1	ENGINE AMBIENT	4	-50 TO 200	+/-5F	0	4	1	1	4	130 F		COORDINATE
TEAMB2	" "											LOCATIONS
TEAMB3												
TEAMB4												

PRESSURES

	PARAMETER			DESIRED				GUAGES		OPERATING		
SYMBOL	DESCRIPTION	QTY	RANGE	ACCURACY	RTM	SS	TRANS	DED	SWITCH	LIMIT	ALARM	REMARKS
PEINL1	ENG INL (MP)	3										
PEINL2	" "											
PEINL3	" "											
PEINL	ENG (TURBO) INL	1	0 TO 30in HgA	2% FS	1	1	1	0	0	NC		
PBOSTA	ENG AIR INLET	1	0 TO 50in HgA	1% FS	1	1	1	1	0	NC		(DIFF) PCELL-LOW
PBOSTD	DIFF. AIR INLET	1	0 TO 50in HgA		1	1	1	0	0	NC		
PEXH	EXH COLLECTOR	1	0 TO 30in HgA	2% FS	1	1	1	0	0	NC		
PFUEL	FUEL AT PUMP INL	1	0 TO 30 PSIG	2% FS	1	0	1	0	0	10 PSIG		
PTINL	TURBO INL (EXH)	1	0 TO 30 PSIA	2% FS	1	1	1	0	0	NC		HIGH TEMP
PTOUTL	TURBINE OUTL	1	0 TO 30 PSIA	2% FS	1	1	1	0	0	NC		HIGH TEMP
PCELL1	CELL AMBIENT	4	0 TO 15 FSIA	[illegible]	4	4	1	0	0	NC		COORDINATE
PCELL2	" "											LOCATIONS
PCELL3	" "											WITH PE22
PCELL4	" "											
PSTART	STARTER AIR	1	0 TO 300 PSIG		1	1	1	1	0	NC		
PSUPPL	SUPPLY AIR	1	0 TO 300 PSIG		1	1	1	1	0	NC		
PRCLI	ROTOR COOL AIR	1	0 TO		1	1	1	0	0	NC		
PFDIS	FUEL DISC	1	0 TO 25 PSIG		1	1	1	0	0			
POIL	OIL PRESSURE	1	0 TO 10 H2O		1	1	1	1				
PFINJ	FUEL INJECTOR	1	0 TO 2000 PSIG		1	1	1	1				

APPENDIX A, CONT'D

MISCELLANEOUS

SYMBOL	PARAMETER DESCRIPTION	QTY	RANGE	DESIRED ACCURACY	RTM	SS	TRANS	GUAGES DED	GUAGES SWITCH	OPERATING LIMIT	ALARM	REMARKS
NENG	ENGINE SPEED	1	0-10000 RPM	0.5% FS	1	1	1	1	0	8000	ADJ(8600)	SPEED SENSE
NTURBO	TURBO SPEED		0-150000 RPM	0.5% FS	1	1	1	1	0	130000	130000	PICKUP
PLA	POWER COMMAND	1	0 to +5 V	STD	1	1	1	1	0	8Volts		
WF	FUEL FLOW	1	0-50 lb/hr	0.5% FS	1	0	1	1	0	NC		
VENGV	ENG VIB VERT	3	0-30g's	STD	3	3	3	3	0	30g's	30g's	TRIAX
VENGH	ENG VIB HORIZ											
VENGA	ENG VIB AXIAL											
ENGCUT	ENG CUT OFF	1	ON/OFF	STD	1	1	1			--	--	
RHUM	REL HUMIDITY	1	0-100%	STD				1		NC		

** NOTE : ALL GUAGE PRESSURES REFERENCED TO CELL AMBIENT PRESSURE

NC = NOT CRITICAL

WATERBRAKE INSTRUMENTATION

SYMBOL	PARAMETER DESCRIPTION	QTY	RANGE	DESIRED ACCURACY	RTM	SS	TRANS	GUAGES DED	GUAGES SWITCH	OPERATING LIMIT	ALARM	REMARKS
NBRK	ROTOR SPEED	1	0-10000 RPM	0.5% FS	1	1	1	1	0	8000	ADJ(8600)	
TORQUE	ENGINE TORQUE	1	0-100 Lb-Ft	+/- 1%	1	1	1	1	0	NC		
WBIV	INLET VALVE POS	1	0-100%	+/- 2%	1	1	1	1	0	NC		
WBOV	OUTLET VALVE POS	1	0-100%	+/- 2%	1	1	1	1	0	NC		
TWBOUT	OUTLET WATER TEMP	1	32^{o}F-125^{o}F	+/- 5^{o}F	1	1	1	1	1	NC		
TWBIN	INLET WATER TEMP	1	32^{o}F-125^{o}F	+/- 5^{o}F	1	1	1	1	1	NC		
PWBSPY	W/B SUPPLY	1	0 TO 200 PSIG		1	1	1	0				
PWBIN	W/B IN PRESS	1	0 TO 100 PSIG		1	1	1	0				
PWBOUT	W/B OUT PRESS	1	0 TO 100 PSIG		1	1	1	0				
WVIBV	VERTICAL VIBS	1	0-10 g's	STD				1	1	NC		
WVIBH	HORIZONTAL VIBS	1	0-10 g's	STD				1	1	NC		
WVIBA	AXIAL VIBS	1	0-10 g's	STD				1	1	NC		

Appendix B

NAVARIWARCENACDIVTRN Data System Uncertainty Estimates

APPENDIX B

DATA SYSTEM UNCERTAINTY ESTIMATES

NAVAL AIR WARFARE CENTER, AIRCRAFT DIVISION, TRENTON
15 AUGUST 1992

PARAMETER	FULL-SCALE RANGE	RESOLUTION	PRECISION	BIAS	UNCERTAINTY
PRESSURE					
PSI SYSTEM	20 psia	.001 psi	.001 psi	.014 psi	.016 psi
	30 psia	.001 psi	.004 psi	.044 psi	.052 psi
	45 psia	.001 psi	.003 psi	.056 psi	.062 psi
	100 psia	.001 psi	.009 psi	.097 psi	.115 psi
	250 psia	.002 psi	.025 psi	.193 psi	.243 psi
	500 psia	.004 psi	.079 psi	.572 psi	.730 psi
SCANIVALVE SYSTEM (1)	7.5 psid	.001 psi	.002 psi	.004 psi	.008 psi
	30 psia	.005 psi	.017 psi	.005 psi	.039 psi
	60 psia	.010 psi	.030 psi	.013 psi	.073 psi
	120 psia	.020 psi	.025 psi	.021 psi	.071 psi
	300 psia	.040 psi	.180 psi	.086 psi	.446 psi
	500 psia	.080 psi	.300 psi	.105 psi	.705 psi
TEMPERATURE (UTR System)	type "E"	0.3 deg F	.25 deg F	1.5 deg F	2.0 deg F
	type "K"	0.5 deg F	.50 deg F	3.0 deg F	4.0 deg F
FORCE (Thrust and Preload)	500 lbf	0.1 lbf	0.5 lbf	0.7 lbf	1.7 lbf
	1000 lbf	0.2 lbf	0.5 lbf	2.0 lbf	3.0 lbf
	5000 lbf	1.0 lbf	2.5 lbf	4.0 lbf	9.0 lbf
	10000 lbf	2.0 lbf	5.0 lbf	8.0 lbf	18.0 lbf
	20000 lbf	4.0 lbf	10.0 lbf	16.0 lbf	36.0 lbf
FREQUENCY	60000 hz	< 1 hz	< .25 hz	< .5 hz	< 1.0 hz
FUEL FLOW (2)					
3/8 - 2.5 gpm	1000 pph	< 0.05 pph	0.4 pph	.25% rdg	3.3 pph at FS
3/8 - 5.0 gpm	2000 pph	< 0.10 pph	0.8 pph	.25% rdg	6.6 pph at FS
1/2 - 10.0 gpm	4000 pph	< 0.20 pph	1.3 pph	.25% rdg	12.6 pph at FS
5/8 - 15.0 gpm	6000 pph	< 0.30 pph	2.0 pph	.25% rdg	19.0 pph at FS
3/4 - 25.0 gpm	10000 pph	< 0.50 pph	2.5 pph	.25% rdg	30.0 pph at FS
1 - 50.0 gpm	20000 pph	< 1.00 pph	5.0 pph	.25% rdg	60.0 pph at FS
1 1/4 - 75.0 gpm	30000 pph	< 1.50 pph	7.5 pph	.25% rdg	90.0 pph at FS
1 1/2 -125.0 gpm	50000 pph	< 2.50 pph	12.5 pph	.25% rdg	150.0 pph at FS
2 -225.0 gpm	90000 pph	< 4.50 pph	22.5 pph	.25% rdg	270.0 pph at FS

(1) *Reference pressures affect uncertainty when delta-p used for absolute.*
5 psia reference: precision = 0.00025 psi; bias = 0.00025 psi
25 psia reference: precision = 0.00350 psi; bias = 0.00350 psi

(2) Fuel flow uncertainty holds for the interval 10% to 100% of range.

Appendix C

Instrumentation List for DGII HFE Test

APPENDIX C

INSTRUMENTATION REQUIREMENTS FOR DGII NFE TEST

TEMPERATURES

SYMBOL	PARAMETER DESCRIPTION	QTY	RANGE F	DESIRED ACCURACY	RTM	SS	TRANS	GAUGES DED	GAUGES SWITCH	OPERATING LIMIT	ALARM	REMARKS	DGI PARAMETER CROSS REF. NO.
TEINL1	ENGINE AIR INLET	4	-25 TO 200	+/-2F	1	1	1	0	1	130 F		TWIST-WIRE T/C	T8
TEINL2	"	"											
TEINL3	"	"											
TEINL	"	"											
TBOOST	ENG AIR INLET	1	-50 TO 200	+/-5F	1	1	1	0	1	130 F		PROBE T/C	
TTROCH	TROCHOID TEMP	1	-25 TO 350	+/-2F	1	1	1	0	1	210 F		SKIN T/C	T1
TURINL	TURBO INLET(EXH)	1	-50 TO 2200	+/-10F	1	1	1	1	1	1710 F	1690 F	PROBE T/C	T11
TUROUT	TURBO OUTLET	1	-50 TO 2200	+/-10F	1	1	1	0	1			PROBE T/C	T12
TFPUMP	FUEL AT PUMP INLET	1	-50 TO 200	+/-2F	1	1	1	0	1	130 F/-25 F --		STD T/C	
TFTNK1	FUEL TANK	1	-50 TO 150	+/-2F	1	1	1	0	0	130 F		STD T/C	
TOILI	ENGINE OIL IN	1	-50 TO 350	+/-2F	0	1	1	1	0	210 F		STD T/C	T6
TOILO	ENGINE OIL OUT	1	-50 TO 350	+/-2F	1	1	1	1	0	260 F	250 F	STD T/C	T5
TENCLO	ENGINE COOLANT OUT	1	-50 TO 300	+/-2F	1	1	1	1	0	210 F	210 F	STD T/C	T3
TENCLI	ENGINE COOLANT IN	1	-50 TO 300	+/-2F	0	1	1	0	1				T2
THEXCH	HEAT EXCHANGER	1	-50 TO 300	+/-2F	1	1	1	1	0	210 F	210 F	STD T/C	
TCELL1	CELL AMBIENT	4	-50 TO 200	+/-5F	1	4	1	1	4	130 F		COORDINATE	
TCELL2	" "				1	1						LOCATIONS	
TCELL3	" "				0	1						WITH PE22	
TCELL4	" "				0	1							
TEAMB1	ENGINE AMBIENT	4	-50 TO 200	+/-5F	0	4	1	0	4	130 F		COORDINATE	
TEAMB2	" "											LOCATIONS	
TEAMB3	" "												
TEAMB4	" "												
TINTAI	INTERCOOLER AIR TEMP IN	1	-50 TO 450	+/-2F	1	1	1	0	1	320 F			T9
TINTAO	INTERCOOLER AIR TEMP OUT	1	-50 TO 350	+/-2F	1	1	1	0	1	210 F			T10
TURWO	TURBO JACKET COOLANT OUT	1	-25 TO 350	+/-2F	1	1	1	0	1				T4
TUROIL	TURBO OIL OUT	1	-25 TO 350	+/-2F	1	1	1	0	1	260 F			T7

APPENDIX C, CONT'D

PRESSURES

SYMBOL	PARAMETER DESCRIPTION	QTY	RANGE	DESIRED ACCURACY	RTM	SS	TRANS	GUAGES DED	GUAGES SWITCH	OPERATING LIMIT	ALARM	REMARKS	DGI PARAMETER CROSS REF. N
PEINL1	ENG (TURBO) INL	4	0 TO 50in HgA	2% FS	1	1	1	1	0	NC		SEND SIGNAL TO MICROPROCESSOR	P2
PEINL2	"	"											
PEINL3	"	"											
PEINL	"	"											
PBOSTD	COMP AIR INLET BOOST PRESS DIFF	1	0 TO 50in HgA	1% FS	1	1	1	1	0	NC		(DIFF) PEINL-LOW	P3-P2
PEXH	EXH COLLECTOR	1	0 TO 30in HgA	2% FS	1	1	1	0	0	NC			
PFUEL	FUEL AT PUMP INL	1	0 TO 30 PSIG	2% FS	1	1	1	0	0	10 PSIG			
PTINL	TURBO INL (EXH)	1	0 TO 70 HgA	2% FS	1	1	1	0	0	NC		HIGH TEMP	P4
PTOUTL	TURBINE OUTL	1	0 TO 50 PSIA	2% FS	1	1	1	0	0	NC		HIGH TEMP	P5
PCELL1	CELL AMBIENT	4	0 TO 15 PSIA	1% FS	4	4	1	1	0	NC		COORDINATE LOCATIONS WITH PE22	
PCELL2	"	"											
PCELL3	"	"											
PCELL4	"	"											
PBOSTA	AIR PRESS AFTER COMPRESSOR	1	0 TO 70 in HgA	1% FS	1	1	1	0	0				P3
POIL	ENG OIL PRESS IN	1	0 TO 120 PSIG	1% FS	1	1	1	1	0	57/73 PSIG	57/70 PSIG		P1

MISCELLANEOUS

SYMBOL	PARAMETER DESCRIPTION	QTY	RANGE	DESIRED ACCURACY	RTM	SS	TRANS	GUAGES DED	GUAGES SWITCH	OPERATING LIMIT	ALARM	REMARKS
NENG	ENGINE SPEED	1	0-8000 RPM	0.5% FS	1	1	1	1	0	6000	ADJ(6500)	SPEED SENSE
PLA	POWER COMMAND	1	0 to +5 V	1.0%	1	1	1	1	0			
WF1	INLET FUEL FLOW	1	0-50 lb/hr	0.5% FS	1	1	1	1	0	NC		
WF2	INLET FUEL FLOW	1	0-50 lb/hr	0.5% FS	1	1	1	1	0	NC		
VENGV	ENG VIB VERT	3	0-30g's	STD	3	3	3	3	0	30g's	30g's	TRIAX
VENGH	ENG VIB HORIZ											
VENGA	ENG VIB AXIAL											
ENGCUT	ENG CUT OFF	1	ON/OFF	STD	1	1	1			--	--	SEND A SIGNAL BASED ON ENGINE OVERSPEED (6500) TO THE SERVO CONTROLER WHICH WILL PULL OUT THE FUEL INJECTOR GOVERNOR ARM TO THE STOP POSITION. ALSO CUT POWER TO THE IGNITION.
PSTART	STARTER PRESSURE	1	0-300 PSIG		0	0	0	1				
PSUPLY	SUPPLY PRESURE	1	0-300 PSIG		0	0	0	1				
TORQRX	REACTION TORQUE	1	0-100 LB-FT	+/- 1%	1	1	1	1	0			
RHUM	REL HUMIDITY	1	0-100%	STD	0	0	0	1		NC		

** NOTE : ALL GUAGE PRESSURES REFERENCED TO CELL AMBIENT PRESSURE

NC = NOT CRITICAL

APPENDIX C, CONT'D

WATERBRAKE INSTRUMENTATION

SYMBOL	PARAMETER DESCRIPTION	QTY	RANGE	DESIRED ACCURACY	RTM	SS	TRANS	GUAGES DED	GUAGES SWITCH	OPERATING LIMIT	ALARM	REMARKS
NBRK	WATERBRAKE SPEED	1	0-8000 RPM	0.5% FS	1	1	1	1	0	6000	ADJ(6500)	
TORQUE	ENGINE TORQUE	1	0-100 Lb-Ft	+/- 1%	1	1	1	1	0	NC		
TORQDS	TORQUE DESIRED	1	0-100 Lb-Ft	+/- 1%	1	1	1	1	0	NC		
WBIV	INLET VALVE POS	1	0-100%	+/- 2%	1	1	1	1	0	NC		
WBOV	OUTLET VALVE POS	1	0-100%	+/- 2%	1	1	1	1	0	NC		
TWBIN	INLET WATER TEMP	1	32oF-125oF	+/- 5oF	1	1	1	1	1	NC		
TWBOUT	OUTLET WATER TEMP	1	32oF-125oF	+/- 5oF	1	1	1	1	1	NC		
WVIBV	VERTICAL VIBS	1	0-10 g's	STD	1	1	1	1	0	NC		
WVIBH	HORIZONTAL VIBS	1	0-10 g's	STD	1	1	1	1	0	NC		
WVIBA	AXIAL VIBS	1	0-10 g's	STD	1	1	1	1	0	NC		
PWBSPY	W/B SUPPLY PRESS	1	0-200 PSIG	2% FS	1	1	1	1	0			
PWBIN	W/B INLET PRESS	1	0-100 PSIG	2% FS	1	1	1	1	0			
PWBOUT	W/B OUTLET PRESS	1	0-100 PSIG	2% FS	1	1	1	1	0			

Appendix D

Instrumentation List for SwRI HFE Test

APPENDIX D

INSTRUMENTATION and DATA ACQUISITION REQUIREMENTS LIST DATE: 08/18/93

ITEM	CATEGORY	ITEM	CATEGORY	ITEM	CATEGORY
0001 - 0999	UNASSIGNED (do not use)	3000 - 3999	FREQUENCY PARAMETER	6000 - 6999	POSITION PARAMETER
1000 - 1999	PRESSURE PARAMETER	4000 - 4999	VIBRATION PARAMETER	7000 - 7999	ANALOG VOLTAGE/ELEC. MEAS.
2000 - 2999	TEMPERATURE PARAMETER	5000 - 5999	FORCE/STRAIN PARAMETER	8000 - 8999	CALCULATION PARAMETER
				9000 - 9999	UNASSIGNED (do not use)

TYP = Measurement Type	CFE = Contractor Furnished	SS = Steady State	SSD = Steady State Display
PLN = Measurement Plane	PRO = Probe/Sensing Element	TR = Transient	RTM = Real Time Monitor
POS = Radial Position	XDR = Transducer	FM = Failure Mode	ALM = Alarm
IMM = Immersion Location	TC = Thermocouple Type	TS = Slow Transient	IND = Control Room Indicator
SOURCE = Measurement Source	BUSCR = Bus Controller	TRN = Normal Transient	TAP = FM Tape Recorder
RANGE = Measurement Range	IN = Input to Bus Controller	THR = High Response	CHT = Chart Recorder
UNITS = Measurement Units	OUT = Output from Bus Controller		COM = Comments exist?

ENGINE: SWRI CUYUNA S/N: 755045 PROGRAM: A/B DEVELOPMENT TEST TE… AREA: LETA 2E REVISION: 1

										CFE				BUSCR					RESP(HZ)								
ITEM	HEADER	PARAMETER DESCRIPTION	TYP	PLN	POS	IMM	SOURCE	RANGE	UNITS	PRO	XDR	TC	IN	OUT	SS	TR	FM	TS	TRN	THR	SSD	RTM	ALM	IND	TAP	CHT	COM
1000	PFILT	INLET FILTER PRES	PD					0-1	PSID						X												
1010	PIND	INLET DIFFERENTIAL PRES	PD					0-1	PSID						X												
1030	PBACK1	EXHAUST #1 BACK PRES	PT					0-25	PSIG						X												
1040	PBACK2	EXHAUST #2 BACK PRES	PT					0-25	PSIG						X												
1050	PAMB	CELL AMBIENT PRESSES	PS					0-25	PSIA						X												
1060	PFUEL	FUEL PRESS OUT OF FLOW METER	PF					0-200	PSIG						X												
1070	PFPUMP	FUEL PRESS OUT OF FUEL PUMP	PF					0-100	PSIG						X												
1100	INGPR	FUEL INJECTOR PRESS																									
1110	CYLPR	PEAK CYLINDER PRESS																									
2000	TENGWI	COOLANT IN TEMP	TF					0-200	F			E			X												
2010	TENGWO	COOLANT OUT TEMP	TF					0-200	F			E			X												
2020	TFIN	FUEL IN TEMP	TF					0-150	F			E			X												
2030	TFOUT	FUEL TEMP OUT OF FLOW METER	TF					0-150	F			E			X												
2040	TIN	INLET AIR TEMP	TF					0-150	F			E			X												
2050	TAIRFL	AIR FLOW MEASURING STATION TE	TF					0-150	F			E			X												
2060	TDYNOI	DYNO COOLANT TEMP IN	TF					0-200	F			E			X												
2070	TDYNOO	DYNO COOLANT TEMP OUT	TF					0-200	F			E			X												
2080	TAMB1	CELL AMBIENT TEMP	TF					0-150	F			E			X												
2100	TEXHA	EXHAUST CYLINDER A TEMP	TF					0-1500	F			K			X												
2110	TEXHB	EXHAUST CYLINDER B TEMP	TF					0-1500	F			K			X												
3000	N1	SHAFT/DYNO SPEED	*					0-10000	RPM						X												
3010	WF1	FUEL FLOW	WF					0-200	PPH						X												
3020	IGNSPK	SPARK RATE	*												X												
5000	TORQUT	SHAFT TORQUE	KX					0-200	IN-LB						X												
5010	SHAPOS	SHAFT POSITION													X												

Total No. of Parameters = 25

T O T A L S

		Steady St.(SS)	=	23			
CFE Probes	= 0	Transient.(TR)	=	0	SS Display	=	0
CFE Transducers	= 0	Fail. Mode(FM)	=	0	Real Time Mon	=	0
		Slow Trans(TS)	=	0	Alarms	=	0
Bus Control IN	= 0	High Resp(THR)	=	0	Control Rm Ind	=	0
Bus Control OUT	= 0				FM Tape Rec	=	0
		Thermocouples:E	=	9	Chart Recorder	=	0
DSR Matrix Availability Factors		:J	=	0			
Mss	= 58	:K	=	2			
Mtr	= 0	TOTAL:	=	11			

M available = 9793

Appendix E

AAI HFE Test Chronology of Events, Phase I

APPENDIX E

AAI HEAVY FUEL ENGINE TEST CHRONOLOGY OF EVENTS, PHASE I

DATE	TEST SUMMARY
17 APRIL 92	We started testing engine S/N 0102-0 which had a 9:1 compression ratio. Engine would not start. We replaced the ECU E-Prom, checked the glow plug and glow plug voltage and the engine still did not start.
20 APRIL 92	We relocated our fuel pressure transducers to get a pressure reading closer to the engine. Installed an AAI high pressure gauge on the fuel manifold to read injection pressure. Fuel pressure checked OK during start attempts. Varied gap in engine speed sensor. Changed ECU E-Prom. Still unable to start engine.
21 APRIL 92	AAI now interfacing with engine controller via laptop computer. AAI checked function of solenoids. Found that pilot injector was missing seat washer, installed washer. Several failed start attempts then the engine started and stalled after the starter was disengaged. Engine started and stalled several more times. Manifold fuel pressure then began to fluctuate between 1500 & 1700 psig. We removed the engine and sent it to AAI for troubleshooting.
23 APRIL 92	Installed second test engine S/N 0101-0. Nine engine start attempts, no start. AAI checked engine and replaced fuse on glow plug. Manifold fuel pressure fluctuated between 1500 & 1700 psig. Engine started and stalled several times. AAI began to suspect our fuel supply system. We increased our fuel supply pressure to 20 psig and tried to start again. The engine started and we cut the engine due to high exhaust temperature. We removed our fuel flow meters from the fuel lines to eliminate a possible restriction. Engine started and stalled several times. Engine had high EGT at idle. Manifold fuel pressure fluctuations between 1500 & 1700 psig while engine running on its own. Constant manifold fuel pressure during engine start attempts. AAI changed the fuel line on the manifold to bypass the 15 psi check valve. The engine did not start.

24 APRIL 92 Due to fluctuations in the engine manifold fuel pressure, we removed all apparent restrictions from the inlet and outlet fuel lines to the engine. Engine was unable to continue running after starter was disengaged. Manifold fuel pressure fluctuated between 1500 & 1750 psig. Return to our original fuel system configuration without the fuel flow meters. Engine did not start. AAI replaced the Sun Valve in the engine fuel manifold. Verified accumulator pressure. Engine did not start. Fluctuating fuel pressures again.

25 APRIL 92 Installed a AAI 12 Volt/14psi/110 gph fuel pump in place of our facility pump. Our facility starter coupling shaft sheared on the first start attempt. Engine S/N 0101-0 removed from the test cell and taken by AAI for evaluation.

27 APRIL 92 AAI tested the engine in their cell and observed similar fluctuations in manifold pressure. AAI then ran the engine using their high pressure fuel supply module and the engine ran OK. AAI is now going to increase the displacement of the engine driven fuel pump to 500 cc/rev to increase the fuel supply.

4 MAY 92 Installed S/N 0101-1 in 6W test cell with 8:1 compression rotor and larger displacement engine fuel pump (500 cc/rev). Engine would not start. AAI varied the fuel delivery using the on line computer to start the engine. The engine would not continue to run once the starter was disengaged. Fuel injection pressure is higher with the larger displacement pump. AAI was able to get the engine to run by varying the fuel delivery using the on line computer. Engine stalled when we applied the waterbrake load. We removed the glow plug and found small pitting on the tip. We installed a new glow plug and continued to try to run the engine. Engine started but did not respond to speed increase command and then stalled. RPM command was fluctuating on the on line computer but not in the control room. Replaced the ECU S/N 41 with ECU S/N 40. Replaced main injector with main injector from Engine S/N 0102-0. Engine did not start.

5 MAY 92 Re-installed the original main injector in engine S/N 0101-1 and isolated the ECU from engine vibrations. Checked the ECU wiring harness. The engine was difficult to start and then started and stalled several times. Replaced the ECU wiring harness. Engine started but did not respond to accel commands. We saw erratic engine speed fluctuations and cut the engine to change the gap on

the speed sensor. Installed new glow plug. Engine started and stalled several times. AAI installed the original E-prom which was delivered in the engine and increased the gap of the speed sensor. Engine was difficult to start and then started and stalled several times. AAI modified fuel delivery and the engine ran steady until load was applied when the engine stalled. AAI increased the speed sensor gap again. The engine started and did not respond to accel commands and then stalled. AAI replaced solenoid valve on main fuel injector. Engine started and ran on the prop load curve up to 5000 RPM, 20 HP & 6000 RPM, 28 HP. We cut the engine to get the exhaust plant on line to begin running our test plan. Completed seven data points before we had to shut down to replace instrumentation. Experienced high EGT at data point # 3 and skipped to point # 4. Engine started and stalled.

7 May 92 Installed new 0.8 GPM flow meters and returned the fuel system to our original configuration. Engine started and stalled several times. Engine started and had high EGT at idle. We cut the engine and reset the gap of the speed pickup to 0.090". Started the engine and advanced the commanded engine speed to 6800 RPM's. The engine oversped and was automatically cut by our overspeed alarm. AAI performed an engine leak down check and found that the pressure had dropped from 60 psig to 20 psig which indicated leaking apex seals. We removed and inspected the glow plug and found pitting on the tip. We removed the engine and disassembled it to inspect the seals. We saw some damage which AAI suspects is due to foreign object damage (FOD). The engine intake (turbocharger inlet) had an air filter installed during all test operations. The air filter would prevent any FOD from entering the engine. We feel that the damage to the engine seals was due to small pieces of the glow plug breaking off.

12 May 92 Install Engine S/N 0102-1 with 9:1 compression rotor. Started engine and noted low fuel injection pressure 1100 vs 1750 psig. Checked the fuel pump and fuel filter. Cleaned fuel filter with compressed air & fuel pump looked OK. Fuel injection pressure increased to 1700 psig. We ran the engine and fuel injection pressure remained at 1750 psig. With less than 30 minutes of operating time on the engine, the rear main oil seal on the engine began to leak oil. We removed Engine S/N 0102-1 and built S/N 0101-2 using the rotor housing from S/N 0102-1.

19 May 92 AAI conducted leakdown check on S/N 0101-2. Engine checked OK. Fuel injection pressure was only 1600 psig vs 1850 psig. Checked both injectors and replaced the sun valve. Replaced the fuel manifold with fuel manifold from S/N 0102-1. Engine started and ran unstable and then stalled. Engine coolant temperature was cooler than expected. AAI replaced engine thermostat. Engine still ran cooler than expected. Engine started and ran unstable below 4000 RPM. Oil consumption was greater than expected.

20 May 92 AAI conducted leak down check. Engine seals degraded slightly but still acceptable. Glow plug looked good. AAI replaced pilot solenoid valve. Engine started and fuel injection pressure was low and engine speed was cycling between 3800 - 4100 RPM. Oil consumption was greater than expected. Removed engine for troubleshooting at AAI.

Appendix F

AAI HFE Test Chronology of Events, Phase II

APPENDIX F

AAI HEAVY FUEL ENGINE TEST CHRONOLOGY OF EVENTS, PHASE II

DATE	TEST SUMMARY
9 Nov 92	Installed S/N 0101-3 in 6W after AAI modified engine ECU to control engine torque as opposed to engine RPM. NAWCADTRN observed engine run at AAI prior to accepting for installation in the 6W test cell. The engine operated at 6200 RPM and 35 HP and responded to accel and decel commands at AAI. During testing at NAWCADTRN, PFINJ was erratic. AAI replaced damaged O-rings on pilot and main solenoid valves. PFINJ pressure fluctuations continued.
10 Nov 92	Continued troubleshooting PFINJ pressure fluctuations. Isolated problem to solenoid valve operation. AAI took injectors and solenoid valves back to plant for bench testing. AAI discovered a broken spring in the main injector. AAI repaired the injector and tested the injectors in another engine at AAI before installing them in the engine at AAI.
12 Nov 92	PFINJ now steady at 1850 psig with repaired injector installed. Engine started and ran at low power several times and then PFINJ fuel pressure would not increase beyond 90 psig. AAI checked the main solenoid valve and the main injector and replaced the main injector block. PFINJ was steadied but still low (1750 psig). AAI replaced main injector. Engine started and was chopped due to EGT's greater than 1600 F. High EGT's due to air in cooling system. Bled air from cooling system and started engine then had to chop to replace fitting on pressure line for Turbocharger Guide Vane Control. Pressure line sheared due to high vibes. Started engine and ran up to 6000 RPM and 30 HP. Changed Prom in ECU to allow speed to increase beyond 6000 RPM. Engine was automatically chopped due to overspeed during slow accel to WOT. Engine started and PFINJ dropped from 1700 psig to 1100 psig. Increased speed control on ECU to 4.0 volts and engine speed only reached 5400 RPM. Increased engine load (CP: 1.85 - 2.0) and engine quit. Replaced pressure line to turbo Inlet Guide Vane Controller. Found slow leak in main injector fuel line and replaced the main injector fuel line. Engine started and PFINJ held steady. Recorded SS Data at 6000 RPM, 24 ft-lb. Dialed speed control on W/B controller to get 7000 RPM. The W/B unloaded the engine causing an overspeed and automatic chop. AAI changed EPROM to limit engine speed to 8000 RPM.

Engine did not start on eight consecutive attempts. Removed glow plug and found large pit in tip and installed a new glow plug. Engine started and ran up to 6500 RPM. Engine oversped and chopped itself automatically. Engine would not start for three start attempts. Checked engine glow plug and glow plug voltage. Engine started and we chopped to end testing for the day.

13 Nov 92 Started engine in speed control mode and began to run engine performance calibrations. Completed calibrations from 3000 to 6000 RPM's. Turbocharger speed fluctuations were noted. Engine oversped and was automatically chopped during accel to 6500 RPM. Engine started and backfired and eventually quit. Replaced glow plug due to pitting at tip after one hour of operation. Started engine on prop load curve. Chopped engine to look for fuel leak around main injector. Tightened main injector. Engine started and stalled twice. Engine started and then oversped during increase to 3.25 volts PLA. Engine oversped once more and then began to stall on accel commands. Engine started and generated a lot of smoke in test cell. Chopped engine to inspect. Glow plug was severely pitted after only 34 minutes of operating time. Installed a different glow plug and engine started and stalled several times. Removed glow plug and installed a new original brand (Beck Arnley Y901R) glow plug. Engine started and twice was chopped because EGT increased beyond 1600 F. Engine started and stalled. Engine started and EGT increased beyond 1600 F. We chopped the engine. AAI reduced fuel delivery on pilot injector. Engine started in speed control mode and stalled during i increase from 1.95 Volts (5000 RPM) to 3.1 Volts. Inspected engine and found loose coil on pilot injector. Engine started and stalled and then would not start in four attempts. Leakdown test on engine showed no compression in engine. Engine was removed and disassembled. The apex seals, rotor, rotor housing, and side walls were all damaged due to FOD from "pitted glow plugs" Air intake filters were used during the entire test. Further details are available in a teardown inspection report.

20 Nov 92 AAI rebuilt the engine with an 8.8 CR rotor. The engine is now designated as S/N 0101-4. The engine was installed in the 6W test cell. The engine did not start during the first two attempts. The main injector was cracked due to over-torque. AAI installed an old injector to verify engine operation. This injector is not calibrated and will not yield optimal performance. Engine started and coolant temp increased beyond 210 F. Bled coolant

system and started engine. Increased speed control voltage from 1.0 to 5.0 volts and the engine did not respond. Stopped testing for the day. AAI to send up a calibrated main injector.

23 Nov 92	Installed newly calibrated main injector in S/N 0101-4. Engine did not start due to low PFINJ fuel pressure. Replaced the solenoid on the main injector and restored the fuel pressure. Engine started and was running with high EGT's (1800 F). AAI stated that the high EGT's resulted from the higher CR rotor. NAWCADTRN decided to discontinue testing until original 8.0 CR rotor engine is installed.
2 Dec 92	AAI rebuilt engine with 8.0 CR rotor. After replacing the solenoid valve on the main injector, the engine started but still operated at high EGT's. NAWCADTRN did not accept engine for continued testing.
3 Dec 92	Engine started at AAI and ran OK at 6000 RPM's with lower EGT's. Engine quit due to intermittent problem with wiring harness. NAWCADTRN sending a spare wiring harness and a HSV to AAI for additional testing.
7 Dec 92	AAI started engine and ran it at 6000 RPM, 26 HP. They reduced the engine to idle speed and it would not accelerate again. AAI conducted a leakdown test and installed a new glow plug (old glow plug was not pitted). The engine leakdown pressure measurement was low (20psi/60psi) but was still acceptable. The engine started and accelerated but did not produce the same power as before. AAI removed the engine and conducted a teardown inspection.
9 Dec 92	AAI disassembled the engine and found no damage. They disassembled the turbocharger and found that the inlet guide vanes were damaged and/or missing and the turbine wheel was damaged due to FOD from the engine and/or the inlet guide vanes. The turbine wheel measured 1.5" in diameter vs the specified 2.4". AAI is sending the turbocharger to Aerodyne Dallas to analyze the failure. NAWCADTRN is also sending the turbocharger from engine S/N 0102 to Aerodyne Dallas for analysis. AAI is going to rebuild the engine and install an old turbocharger Model 53000 which was used during the development testing.
15 Dec 92	NAWCADTRN rep visited AAI to witness acceptance test prior to accepting engine for installation. Engine started and operated for approximately one hour.

Engine achieved a maximum of 5500 RPM and 19 ft-lb. Engine speed fluctuated somewhat with constant PLA setting.

18 Dec 92 Installed engine S/N 0101-5 (build 5) in the 6W test cell. Engine started easily and operated well. The response to accel commands was not linear. The engine did not accel from 1.0 to 3.0 volts. When the engine finally did accelerate, it oversped and was automatically chopped. The engine started and ran well at 7500 Ft and 44 deg F. We completed performance calibrations from 3000 - 5000 RPM at sea level and 7500 Ft. We operated the engine for 4.3 hours. We limited our calibrations to 5000 RPM due to the lack of speed control beyond 5000 RPM. We are going to modify our waterbrake response rate and change the ECU software to allow speed control beyond 5000 RPM.

21 Dec 92 The engine started and operated well. We were modifying our waterbrake control to allow better control of engine speed when a bolt which secured the torque load cell sheared. Our engine speed signal was intermittent. We stopped testing to replace the speed pickup and secure the torque load cell.

23 Dec 92 We secured the torque load cell and performed an "end check" on the torque calibration curve. We replaced the engine speed sensor. The engine response to accel commands was still non-linear. The engine would begin a rapid accel only after advancing the PLA from 20% to 60%. We were still unable to control the rapid engine accelerations with our automatic load control system. We shut the engine main power off when the engine speed exceeded 7500 RPM. The aluminum mounting plate on the lower end of the engine cracked.

30 Dec 92 Spare mounting bracket installed. Engine re-aligned and torque cal performed. Engine torque began to fluctuate while trying to hold 5000 RPM and the engine stalled after increasing the max allowable RPM to 5500. Performed a compression check and found that the engine had lost compression from the morning reading.

5 Jan 93 We performed a teardown and inspection of the engine. The trochoid housing had carbon buildup from the pilot injector and glow plug location all the way down to the exhaust port. AAI reported that the apex seal springs were flatenned at a location corresponding to a mottled spot on the trochoid housing. We found two of the side seals on the

anti-propeller end of the engine and one side seal on the propeller end were stuck at the leading edge. Several small cracks were noted on the anti-propeller end plate. The cracks are due to thermal stress and they do not appear to be growing. The side seals are sticking because of combustion blow-by due to poor sealing between the rotor and the end plates. AAI is going to rebuild this engine with new springs and seals.

15 Jan 93 AAI rebuilt the engine S/N 0101-3 and reported that the clearance between the rotor and the end plate was 0.020". The maximum allowable clearance is 0.013". The damage found on the previous engine teardown and inspection can be explained by this excessive clearance. The trochoid housing would have to be ground down to achieve the proper clearance. We have installed the engine now designated as S/N 0101-6 and are going to run it without modifying the clearance. We spent the day troubleshooting a vibration problem on the installation. High vibrations were causing bolts to back out, instrumentation lines to shear, and connectors to fall off. We stopped testing when the torque load cell bolt sheared.

19 Jan 93 We checked the alignment of the engine and waterbrake and found that the alignment had changed. The flex coupling was badly worn due to the misalignment. Replaced the flex coupling and re-aligned the engine.

21 Jan 93 Performed a vibration analysis on the engine and waterbrake installation. The vibrations were at a normal level. We ran the engine on a propeller load curve and achieved 32 HP at 5900 RPM with low fuel consumption. The engine could not accelerate beyond 6200 RPM. After one hour of running, the glow plug tip broke off and the engine stalled. The tip remained in the trochoid housing and did not damage the rotor or the apex seals. However, the engine did lose compression due to sticking side seals. We removed, disassembled, and inspected the engine.

Appendix G

AAI Data Reduction Equations

Appendix G

AAI DATA REDUCTION EQUATIONS

```
TCELAR = TCELLA + RANK

OMEGA = (PEINL * 1.33) / (TCELLA + 459.7)

RHO = OMGEA / 32.2

HPSHFT = 1.904E-4 * TORQUE * NENG

HPENG = HPSHFT

DELR = PEINL / PEINLDS

THER = TCELAR / TCELDSR

STHER = THER**.5

HPENGR = HPENG / STHER

XNENGR = NENG / STHER

CALL HEIGHT(PEXH,ALT,ERR)

SGFUEL = POLY(TFTNK,CN(26),1)
```

Appendix H

DGII Data Reduction Equations

APPENDIX H

DGII DATA REDUCTION EQUATIONS

```
RANK = 459.7

TCELAR = TCELLA + RANK

TEINAR = TEINLA + RANK

OMEGA = (PEINLA * 1.33) / (TEINAR)

RHO = OMEGA / 32.2

HPSHFT = 1.904E-04 * TORQUE * NENG

HPENG = HPSHFT

DELR = PEINLA / PEINDS

DELC = PEINLA / 29.92

TCLDSR = TCELDS + RANK

TEIDSR = TEINDS + RANK

THER = TEINAR / TEIDSR

THEC = TEINAR / 518.7

STHER = THER**.5

STHEC = THEC**.5

HPENGC = (HPENG*STHEC) / DELC

HPENGR = (HPENG*STHER) / DELR

WFA = (WF1 + WF2) / 2

WFAR = WFA / (STHER * DELR)

BSFC = WFA / HPENG

XNENGR = NENG / STHER

XNENGC = NENG / STHEC

CALL HEIGHT(PEXH,ALT,ERR)

SGFUEL = POLY(TFPUMP,SG,VISC)
```

Appendix I

SwRI Data Reduction Equations

APPENDIX I

SwRI Data Reduction Equations

AIRFLOW:

```
dP   = DIFFERENTIAL PRESSURE ACROSS ELEMENT
Pf   = INLET PRESSURE ("Hg ABSOLUTE)
Tf   = INLET AIR TEMP (DEG F)
B    = 5.48785E+01
C    = -3.80317E-01
VISC = (14.58*((459.67+Tf)/1.8)^(3/2))/(110.4+((459.67+Tf)/1.8)
ACFM = B*dP+C*(dP^2)*181.87/VISC
SCFM = ACFM*(Pf/29.92)*(529.66/459.67+Tf)
```

POWER:

```
T = TORQUE
RPM = ENGINE SPEED
HP = T*RPM/5252
CHP = HP*((29.92/Pf)*(((Tf+459.67)/459.67))^0.7)^0.3
```

MISCHELANEOUS:

```
FUEL FLOW =  FF
BSFC = FF (lb/hr)/HP
A/F = SCFM*4.494/FF
```

Appendix J

DGII HFE S/N 038 Teardown Inspection

APPENDIX J

DGI HFE S/N 038 TEARDOWN INSPECTION

1. SIDE HOUSING-PTO SIDE (WITH PLANETARY GEAR): Three gear teeth were broken off and the remaining teeth are chewed up.

2. ROTOR ASSEMBLY: Apex seals are wedged into rotor apex due to extreme heat (seized); Journal bearing is chewed up; Housing for journal bearing is cracked at location of rotor balancing hole.

3. APEX SEALS (3): Seals are stuck in the rotor apex due to extreme heat (seized).

4. SIDE SEALS (3): Visually Acceptable

5. SPRINGS FOR SEALS (ALL): Side springs are visually acceptable. Condition of apex springs unknown due to apex seals being stuck in rotor apex.

6. OIL PUMP ASSEMBLY: Impeller has scratches along surface of outer lobes. Impeller housing has scratches along inner surface.

7. TROCHOID (ROTOR HOUSING): Completely cracked into two pieces. Coated with carbon. Grooves cut in near intake and spark plug locations.

8. SHAFT KEYS: Visually Acceptable

9. COMPLETE O-RING PACKAGE: Visually Acceptable

10. OIL CONTROL RINGS FOR ROTOR (1) The ring located closest to the planetary gear was scored and cracked. The scoring and crack are perpendicular to the curvature of the ring.

11. SIDE HOUSING-WATER PUMP SIDE: The surface was smooth except for a 1" x 1/8" scratch. The scratch was not deep.

12. SHAFT ECCENTRIC: Slightly scored along the circumference (approximately a 60 degree arc).

13. TURBINE INLET WATER JACKET PIPE: The weld seam on the inner concentric pipe (separates the water and air flow) was open.

14. ALL CAM SHAFT AND WATER PUMP GEAR ASSEMBLIES: Visually Acceptable

15. WATER PUMP ASSEMBLY: Visually Acceptable

16. FUEL INJECTION SYSTEM: Visually Acceptable

17. OIL PAN ASSEMBLY: Visually Acceptable

18. TURBOCHARGER: Visually Acceptable

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